DOE/MC/21181-1950, Vol. 7
(DE86006637)

Geological Evolution and Analysis of Confirmed or Suspected Gas Hydrate Localities

Volume 7. Basin Analysis, Formation and Stability of Gas Hydrates in the Columbia Basin

By
P. Finley
J. Krason

Work Performed Under Contract No.: DE-AC21-84MC-21181

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

By
Geoexplorers International, Inc.
5701 E. Evans Avenue
Denver, Colorado 80222

March 1986

PREFACE

This document is Volume VII of a series of reports entitled "Geological Evolution and Analysis of Confirmed or Suspected Gas Hydrate Localities." Volume VII is titled, "Basin Analysis, Formation and Stability of Gas Hydrates in the Columbia Basin." This report presents a geological description of the Columbia Basin, including regional and local structural settings, geomorphology, geological history, stratigraphy, and physical properties. It provides the necessary regional and geological background for more in-depth research of the area. Detailed discussion of bottom simulating acoustic reflectors, sediment acoustic properties, distribution of hydrates within the sediments, and the relation of hydrate distribution to other features such as salt diapirism are also included. The formation and stabilization of gas hydrates in sediments are considered in terms of phase relations, nucleation, and crystallization constraints, gas solubility, pore fluid chemistry, inorganic diagenesis, and sediment organic content. Together with a depositional analysis of the area, this report is a better understanding of the thermal evolution of the locality. It should lead to an assessment of the potential for both biogenic and thermogenic hydrocarbon generation.

Project Manager
Gas Hydrates

Acknowledgements

Geoexplorers International Inc. and the authors are grateful to the U.S. Department of Energy - Morgantown Energy Technology Center for the opportunity to participate in the gas hydrate research program. Critical review of this report by Kathryn Dominic and Rodney Malone of DOE-METC is highly appreciated. Charles Komar expedited printing of this report.

Troy Holcombe of the National Geophysical Data Center reviewed this report and engaged in fruitful discussions of Caribbean geology during its preparation.

Many people assisted the authors in assembling the geophysical data used in this report. Patricia Ganey of the University of Texas Institute for Geophysics provided unpublished seismic sections of the study region. James Griffin from the University of Rhode Island Graduate School of Oceanography searched the archives and supplied the original seismic records from the Colombia continental margin. Bill Dunkle provided data from an early Woods Hole Oceanographic Institution cruise. Kathy O'Day and Dan Metzger from the National Geophysical Data Center assisted the authors in locating and retrieving seismic lines and critical navigation data.

The illustrations in this report were expertly drafted by Margaret Krason of Geoexplorers International, Inc. Joan Gross typed this paper.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

LIST OF FIGURES

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

LIST OF TABLES

EXECUTIVE SUMMARY

The interrelationships of geologic environments and gas hydrates were investigated by a thorough basin analysis in the southwestern Caribbean region. The diverse geologic factors and abundant indirect evidence of gas hydrates makes the Colombia Basin an ideal region for gas hydrate study.

This study was performed for the U.S. Department of Energy - Morgantown Energy Technology Center by Geoexplorers International, Inc. as part of a worldwide evaluation of 24 offshore sites where the presence of gas hydrates has been confirmed or inferred. The results of this study are summarized in Table 1.

The study region is located north of Panama and Colombia and southwest of Hispanola. The Colombia Basin is bounded to the south by the continental margins of Panama and Colombia. The Nicaragua Rise, South Haitian Borderland, and Beata Ridge border the Colombia Basin to the northwest, north, and east respectively. These bordering uplifts were included in the study region to better evaluate the Colombia Basin itself.

The Colombia Basin consists of deep abyssal plains and two large submarine fâns. The continental margins are structurally deformed and resemble convergent plate boundaries. The Nicaragua Rise and Beata Ridge are block-faulted, uplifted terranes with appreciable sediment accumulations only in graben settings.

Shallow coring has indicated that the fan, abyssal plain, and continental margin are covered with turbidites and hemipelagic sediments. Pelagic carbonates cover the Nicaragua Rise, Beata Ridge, and small uplifts on the abyssal plain. Cores of deeply buried sediments have been recovered only from the pelagic areas, but suggest that the turbidites and hemipelagic sediments which cover most of the study region are rich in organic matter and may have high gas generative potential. Seismic stratigraphic interpretations have confirmed the great extent of these possibly organic-rich turbidites.

The study region has experienced considerable structural deformation which has continued to the present. The deformed belts which make up the continental margins show compressive features in seismic profiles, but must also have sustained some strike slip motion. The Pliocene collision of Panama and Colombia was a major factor controlling the present structure of the basin. The study region is the site of extensive mud diapirism.

Seismic lines indicate the presence of gas hydrates in the region. Multichannel and some single channel seismic lines of the continental margin display bottom simulating reflectors (BSRs) which are interpreted as marking the base of the gas hydrate stability zone. The BSRs are very widespread over the entire continental margin beneath water depths of 900 - 4,000 m. BSRs were also found at two sites in the abyssal plain.

No gas hydrates have been recovered from the study region, but abundant biogenic methane was found in Pliocene turbidites beneath the abyssal plain. The pelagic sediments covering the uplifted areas contain low levels of organic carbon and have very low gas generative potential. High organic carbon levels were found in the few available analyses of the hemipelagic sediments and turbidites of Late Cretaceous through Pliocene age.

Geothermal gradients over the continental margins vary from 3.1 to 4.1° C/100 m based on the subbottom depths of BSRs and reported bottom water temperatures. Gas hydrates composed of biogenic methane should be stable to a minimum water depth of about 580 m. Gas hydrates composed of typical thermogenic natural gas should be stable under water deeper than 300 - 400 m in the Colombia Basin.

Deeply buried rocks of the abyssal plain near the continental margin of Colombia are thermally mature with respect to oil and gas generation. If migration paths exist, the gas hydrates of the marginal deformed belt offshore of Colombia may contain thermogenic gas. Sediments offshore of Panama appear to be too thin to have achieved thermal maturity.

A synthesis of relevant geological factors indicates that the marginal deformed belts and the abyssal plain sediments have the greatest potential for containing large volumes of gas trapped in the form of hydrates. The Nicaragua Rise has essentially no hydrate potential. The Beata Ridge and South Haitian Borderland are assigned a low overall potential for gas hydrates, but hydrates may exist locally near permeable migration routes.

Sampling the sediments of the abyssal plain and continental margins by deep drilling could verify these interpretations by providing needed data on sediment geochemistry. Reprosessing existing seismic data and collecting more seismic information would permit more precise assessment of potential gas resources trapped in and beneath gas hydrate bearing zones.

TABLE 1, Summary Data of Basin Analysis, Formation and Stability of Gas Hydrates in the Columbia Basin, is located in the pocket at the end of the report.

INTRODUCTION

Gas hydrates are solid substances composed of gas molecules trapped within cages of water molecules. Gas hydrates can be formed from gas and water at high pressures and low temperatures when a sufficiently high concentration of gas exists. Conditions favorable for gas hydrate formation and preservation are found in some continental margin and deep sea sediments where adequate hydrocarbon gases are available. Large quantities of natural gas with possible resource potential may be trapped in and beneath offshore gas hydrates.

This report presents the results of a study on the geological factors which control the distribution of gas hydrates in the Colombia Basin occupying the southwestern part of the Caribbean region. This study is a part of a larger project being performed for the U.S. Department of Energy (DOE) - Morgantown Energy Technology Center (METC) by Geoexplorers International, Inc. The main purpose of the project is to evaluate the geological environments of gas hydrate formation and stability and to make preliminary assessments of gas resources associated with gas hydrates.

Previous studies by Geoexplorers International have examined the formation, stability, and occurrence of gas hydrates in four regions along passive continental margins. The Colombia Basin study region, composed of the basin and bordering uplifts, presents a wide variety of geological environments for study, including convergent plate boundaries; abyssal plains; and areas of compressional, strike-slip, and extensional deformation. Due to this wide range of geological conditions present in a single study region, the relative influence of different factors on gas hydrate distribution can be examined. The results of this study on the Colombia Basin may be of use as a model for assessing gas hydrate potential in other regions where similar geologic environments exist, but relevant data on gas hydrate presence are not gathered and systematically evaluated.

This report is based on from publicly available information. Information on the southwest Caribbean region abounds in the literature. The complex geology of the Colombia Basin is not easily explained by simple theories; many studies were conducted to resolve these discrepancies. The proximity of the study region to the prolific hydrocarbon producing fields of Venezuela and Colombia has fostered additional research, much of which remains proprietary. In addition to abundant published information, unpublished geophysical data were incorporated into this report.

This report is presented in two parts:

Part I - Basin Analysis, provides a review of the geology of the Colombia Basin study region with an emphasis on those processes which may have had a direct bearing on possible gas hydrate presence.

Part II - Formation and Stability of Gas Hydrates, examines in detail the evidence for gas hydrates in the study region, sediment geochemistry, thermal conditions, possible host and source lithologies, and the potential for thermogenic and biogenic hydrocarbon generation. By evaluating these factors it became possible to rank areas within the study region as to gas hydrate potential and to derive gas hydrate resource estimates.

Although efforts were made to include all pertinent references, the authors do not claim that this report constitutes an exhaustive review of Caribbean regional geology. Some relevant publications may not have been consulted in preparing this report due to our own oversight.

PART I

BASIN ANALYSIS

The Colombia Basin study region (Figure 1) is composed of eight geological provinces (Case et al., 1984). Each of these areas displays a distinct combination of structure, sedimentation, and paleogeographic history.

The sedimentation patterns of the study region can be deduced from core data and seismic reflection profiles. Five Deep Sea Drilling Project (DSDP) drill holes and many shallow piston cores provide direct, but limited data on the age and lithology of sediments in the region. The DSDP cores were taken from locations with sedimentary sections atypical of the basin as a whole. Shallow piston cores, while more evenly distributed, only sampled Quaternary sediments. Seismic lines have been of use in extending interpretations on sedimentation from the cores to region-wide syntheses. Seismic stratigraphic studies are limited by few quality seismic lines and lack of drill hole control of the age of the most common seismic units.

The structure of the study region is complex and open to different interpretations. The anomalously thick allochthonous oceanic crust of the area and overlying sediments have been deformed to result in the present regional geomorphologic configuration of a deep basin bounded on all sides by faulted uplifts. The timing, style, and cause of this repeated deformation is controversial. Areas of active mud diapirism are found in the study region.

Location

The Colombia Basin study region is located in the Caribbean Sea north of Colombia and Panama (Figure 1). The Colombia Basin, a 400,000 km^2 marginal basin, is bounded on the north by the Nicaragua Rise, a northeast trending structural high, and the South Haiti Borderland to the northwest. The Beata Ridge, a north-northeast trending block-faulted uplift separates the Colombia Basin from the Venezuela Basin to the east. The Beata Ridge is terminated to the south by the deep west trending Aruba Gap located 150 km north of the Colombia coast. The eastern limit of the region being considered in this report is the 72° W meridian. The majority of the Colombia Basin is overlain by deep water. Approximately 300,000 km^2 of sea floor is covered by more than 3,000 m of water. Water depths average 1,500 m over the Nicaragua Rise and 2,600 m on the Beata Ridge.

FIGURE 1, Bathymetric Map of the Columbia Basin Study Region, is located in the pocket at the end of the report.

Study Areas

Case et al. (1984) divided the Caribbean into geological provinces which differ in structural style; rock thickness, lithology, or age; physiographic expression; and other characteristics. In this report, the geological provinces defined by Case et al. (1984) are used to subdivide the complex study region into smaller areas.

The Colombia Basin study region consists of eight geologically distinct areas (Figure 2). The vast abyssal plain of the basin is overlapped by terrigenous sediments of two large deltaic fans. The southern margin of the basin seaward of the coasts of Colombia and Panama is composed of two accretionary deformed belts related to the convergence of the Caribbean and South America plates. The abyssal province is rimmed on the north and east by uplifted terranes which are complexly faulted.

Abyssal Plain

The Colombia Basin abyssal plain (Figure 2) covers the largest portion of the study region. The abyssal plain consists of expanses of stratified turbidites and pelagic oozes. Although the plain is largely featureless, some surface relief is evident on the bathymetric map (Figure 1) between 77° W - 81° W and 11° W - 13° W. The contacts of the abyssal plain with the distal portions of the fan provinces are largely gradational, and the boundaries shown in Figure 2 are somewhat arbitrary.

Submarine Fans

Two large submarine fans extend deep into the Colombia basin.

The **Panama-Costa Rica Fan** is developed from sediments deposited by many relatively small Panamanian rivers. This feature is not well studied; no published investigations on the Panama-Costa Rica Fan are available.

The **Magdalena Fan** is much larger and better studied than the Panama-Costa Rica Fan. The Magdalena Fan is made up of deposits from the Magdalena River and the Sinu River (Figures 1 and 2). Recent work by Kolla et al. (1984), utilizing single channel and multichannel seismic data and piston coring results, indicates that the roughly arcuate feature with a radius of about 230 km can be divided into three zones. The upper fan is characterized by steep slopes (1:60 - 1:110) and well developed channels and levees with as much as 100 m relief between the channel bottoms and adjacent levees. The overbank deposits in the upper fan often exhibit very long wavelength (1 km) sediment waves. The middle fan complex has a gradient between 1:110 and 1:200 with much smaller channels and levees. The lower fan is nearly flat, with a gradient of less than 1:200. The featureless surface of the lower fan is interrupted by small channels with no identified levees.

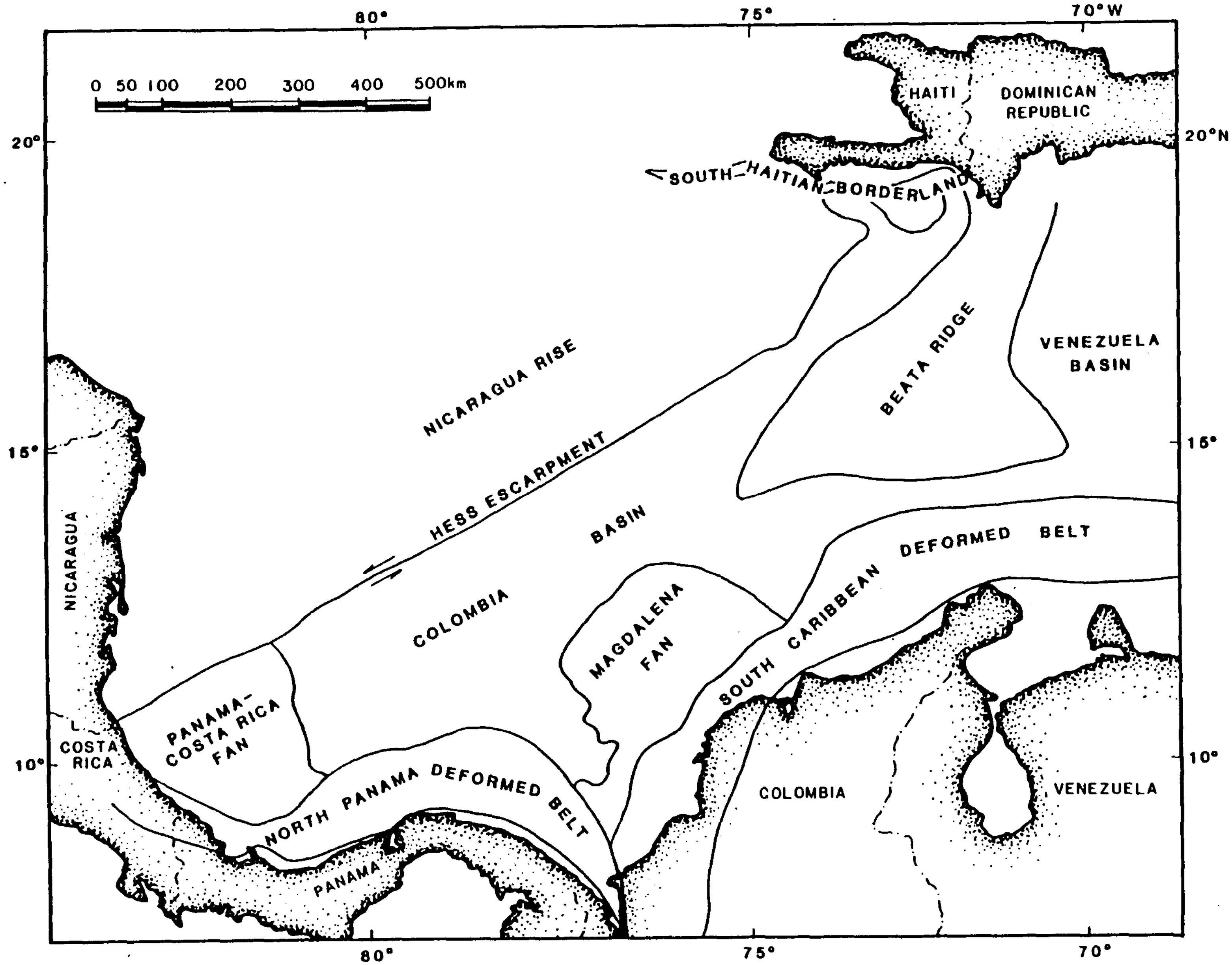


Figure 2. GEOLOGICAL PROVINCES OF THE COLOMBIA BASIN STUDY REGION
After Case et al., 1984

Deformed Belts

The margin of the Colombia Basin offshore of Panama and Colombia is dominated by two 100 km wide belts of faulted and folded sediments. These marginal deformed belts of the Colombia Basin are morphologically similar to the accretionary wedges and forearc basins found landward of oceanic trenches. The Colombian belts differ from classical convergent margins in that andesitic volcanism and well defined seismic Benioff zones are absent. This fact led Lu and McMillen (1983) to refrain from referring to these areas as subduction zones.

Case and Holcombe (1980) divided the Colombia Basin marginal deformed belts into two well differentiated terranes.

The **North Panama Deformed Belt** extends approximately 800 km along the Caribbean coasts of Costa Rica and Panama (Figure 2). This belt averages 100 km in width (Case et al., 1984) and generally parallels the coastline.

The **South Caribbean Deformed Belt** is separated from the North Panama Deformed Belt by a north trending fault interpreted by Mann and Burke (1984) as a suture zone. The South Caribbean Deformed Belt continues northeastward offshore of Colombia and Venezuela for approximately 1,200 km. The South Caribbean Deformed Belt possesses a much steeper slope than the North Panama Deformed Belt near the suture, but near the Colombia-Venezuela border the deformed belt is as broad as that offshore of Panama (Figure 1).

Nicaragua Rise

The Nicaragua Rise is an area of shallower water depths (200 - 5,000 m) which forms the northwestern limit of the Colombia Basin. The Nicaragua Rise and the Colombia Basin are separated by the steep, exceedingly linear Hess Escarpment (Figures 1 and 2). The surface of the Nicaragua Rise is draped with sediments which obscure the relief of block faulted basement uplifts (Holcombe, 1977).

A cross section showing the spatial relationship of the Nicaragua Rise, the Panama-Costa Rica Fan, and the North Panama Deformed Belt from the western part of the study region is presented in Figure 3.

South Haitian Borderland

The geology of the northeast border of the Colombia Basin, the South Haitian Borderland (Figure 2), has not been well investigated. The density of the bathymetric contours in Figure 1 suggests a margin with a slope similar to that of the west flank of the Beata Ridge.

Beata Ridge

The Beata Ridge is a broad triangular uplifted province stretching from Hispanola to near the South Caribbean Deformed Belt (Figure 2). The area is

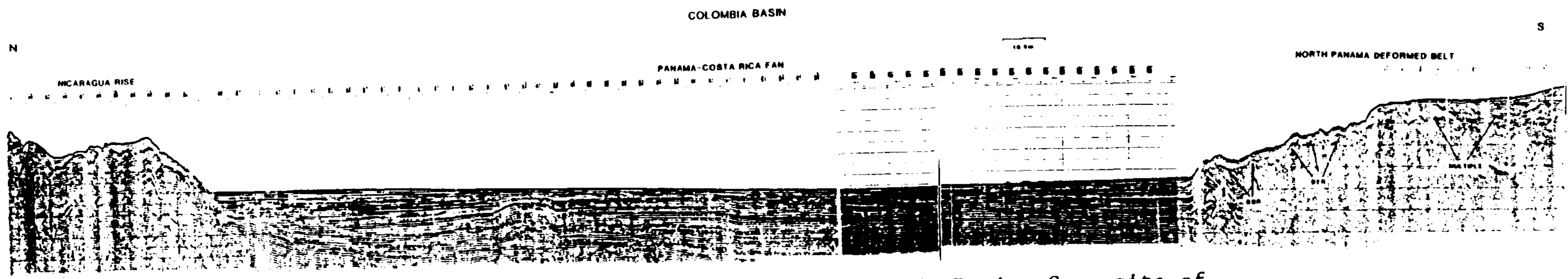


Figure 3. Seismic Cross-Section of Study Region. Composite of unpublished U.T.I.G. seismic lines NR-1, CB-2, and PN-1

characterized by differentially uplifted fault blocks with thick sediment prisms in grabens (Roemer et al., 1973). The western flank of the Beata Ridge facing the Colombia Basin is steeper than the eastern slope.

Sediments

The sediments of the Colombia Basin are of two principal types, pelagic carbonate sediments and clastic deep sea terrigenous sediments (Holcombe, 1977; Lu and McMillen, 1983). Pelagic basin-floor sediments are found on part of the abyssal plain, on the bordering Beata Ridge and Nicaragua Rise, and on isolated structural highs throughout the basin. The terrigenous sediments cover the two deep sea fans and areas of the sea floor receiving distal turbidites from the fans. The Holocene sediments of both types have been well characterized with shallow core and dredge samples. Deep holes penetrating the Tertiary and early Quaternary age sediments are largely in the pelagic sedimentary lithofacies. The few recovered Tertiary turbidite samples have shown high biogenic gas generating potential.

Deep Sea Drilling Project Cores

The Deep Sea Drilling Project (DSDP) cored at five sites in and adjacent to the Colombia Basin (Edgar et al., 1973; Prell et al., 1983; Figure 1). Leg 15 drilled three holes in the marginal rises (151, 152, 153) and one hole in the Colombia Basin (154). On Leg 68, the R/V Glomar Challenger returned to core in the Colombia Basin near Site 154 to test the newly developed hydraulic piston corer at Site 502.

Site 151 was drilled high on the west flank of the southern Beata Ridge (Figure 1). This site was selected because the thin pelagic sediment cover allowed the rock corresponding to a basinwide seismic reflector to be cored at a shallow subbottom depth (Edgar et al., 1973). The location selected was in 2,029 m of water on a prominent high (Figure 4). The hole was drilled to basalt at 381 m.

The recovered sediments were divided into two units (Figure 5). The upper unit is composed of 370 m of poorly consolidated pelagic carbonate oozes and marls. A lower unit, bounded by a disconformity representing about 15 m.y., consisted of hard, silicified Cretaceous clay with abundant organic matter (Figure 5). The disconformity was interpreted to represent an extended period of strong current activity, but showed no evidence of subaerial exposure.

The Paleocene to Holocene section from the sea floor to 365 m subbottom has a very low potential as a gas hydrate source sediment. The organic carbon content of the Cenozoic section is generally very low, ranging from 0 to 0.3% with a mean value of 0.1% (Bode, 1973; Figure 5). Although gas hydrates have been inferred to exist in sediments with mean organic carbon content as low as 0.3% in the Gulf of Mexico (Krason et al., 1986), biogenic methanogenesis at a level sufficient to adequately saturate pore fluids to form gas hydrates seems unlikely in a sediment with a mean organic

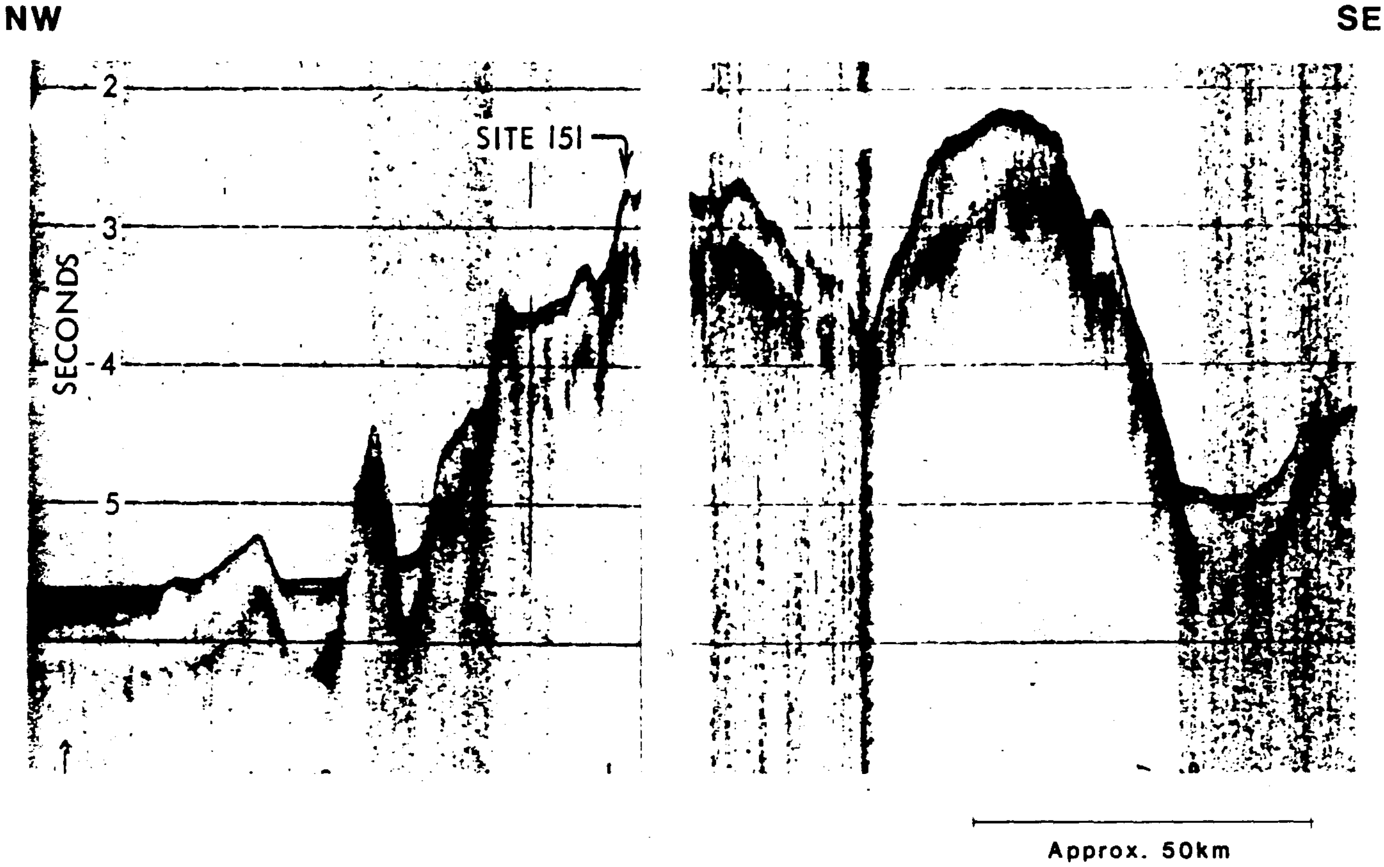


Figure 4. SEISMIC PROFILE OF BEATA RIDGE SHOWING LOCATION OF DSDP SITE 151

After Edgar et al., 1973

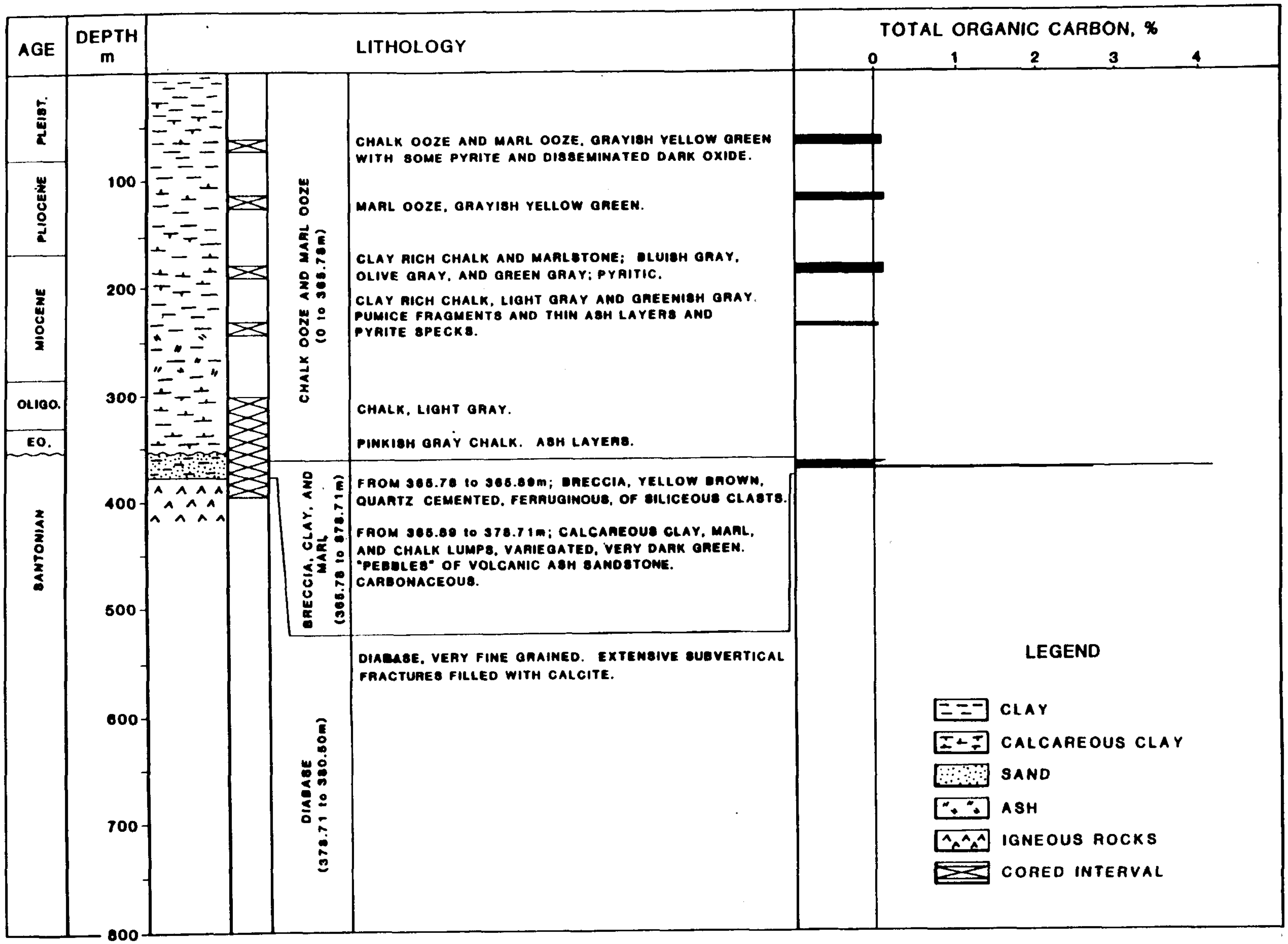


Figure 5. LITHOLOGY AND ORGANIC CARBON CONTENT, DSDP SITE 151

After Edgar et al., 1973

content of 0.1%. Accordingly, the site report gives no indication of the presence of any gas (Edgar et al., 1973). Core photographs display none of the gas expansion voids expected of gas charged and/or hydrated sediments. Since the shallowest core of these carbonate sediments, from 60 m subbottom, already displayed the pyrite and dark green color typical of an anoxic reducing environment, no estimate can be made on the thickness of the aerobic or sulfate-reducing zones.

The Santonian-Paleocene unconformity at 365 m subbottom is marked by a distinct, lithified, silicified carbonate "hard ground." This was interpreted to represent scouring by strong currents in a well oxygenated environment (Edgar et al., 1973). The implication is that during the time span represented by the unconformity, regional geography changed and substantially altered the current flow patterns, or that the area was elevated into different current regimes, or both.

The 10 m section of Cretaceous sediments between the unconformity and Cenomanian (?) basalt consists of ferruginous foraminiferal sandstones, marls and carbonate oozes. Large pyrite concretions were recovered from lenses in the fine grained sediments. Small fragments of volcanic sandstone were found near the base of the section. The most remarkable aspect of this Cretaceous section is the exceedingly high organic carbon content of the sediments. A sample from 2 m beneath the unconformity had a total organic carbon (TOC) value of 4.2%. The only other Cretaceous sample tested, from 2 m above the basaltic basement, contained 2.7% TOC. No visibly distinguished carbonaceous plant or animal remains were mentioned. Further work to type the kerogen optically was not pursued. The foraminiferal sands (possibly turbidites) and the organic richness of the sediments were interpreted by the project scientists to indicate that the sediments were deposited in a topographic low, opposite of the present bathymetric configuration. This view supports the possibility of the Campanian and Maestrichtian being a time of local or regional tectonism. An alternative interpretation of the organic-rich subunconformity sediments, proposed by Edgar et al. (1973), is that rather than accumulating only in a bathymetric low, organic rich sediments were widely deposited and preserved on a flat sea floor during a period of regional anoxia. Waples (1983), while downplaying the role of anoxia in the accumulation of organic-rich Cretaceous shales in general, did present evidence from the North Atlantic of similar, highly carbonaceous sediment deposited in Santonian time.

The deepest rock penetrated at Site 151 was a vesicular basalt. The contact between the sediments and basalt was not recovered, complicating interpretation of the early history of the southwestern Beata Ridge.

Site 152 was located on the lower flank of the Nicaragua Rise (Figure 6) about 180 km northwest of Site 151 (Figure 1), in 3,899 m of water. The site was drilled to a depth of 477 m (Edgar et al., 1973). The hole bottomed in basalt after drilling 472 m of calcareous ooze, chalk, and limestone.

No cores were taken from subbottom depths of less than 160 m. The recovered sections were dated paleontologically as Campanian to early Eocene (Figure 7). The sediment cores were generally composed of nannofossils and foraminifera. The degree of test preservation indicates that accumulation took place well above the carbonate compensation depth (Edgar et al., 1973). Occasional ash bands increased downward. Narrow zones of terrigenous clay admixed with the dominant carbonate sediment were also identified.

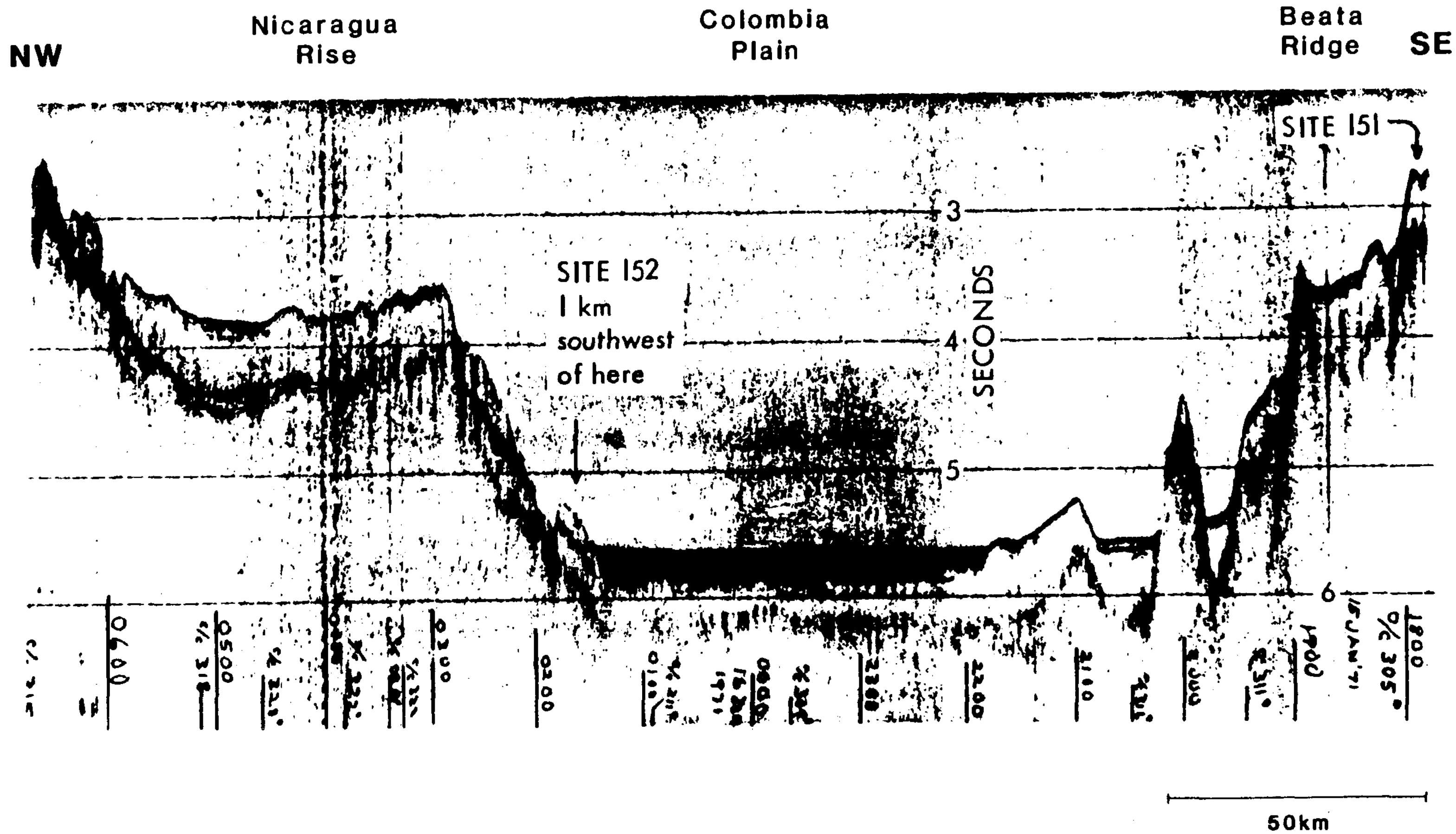


Figure 6. SEISMIC PROFILE OF COLOMBIA BASIN SHOWING LOCATION OF DSDP SITE 152

After Edgar et al., 1973

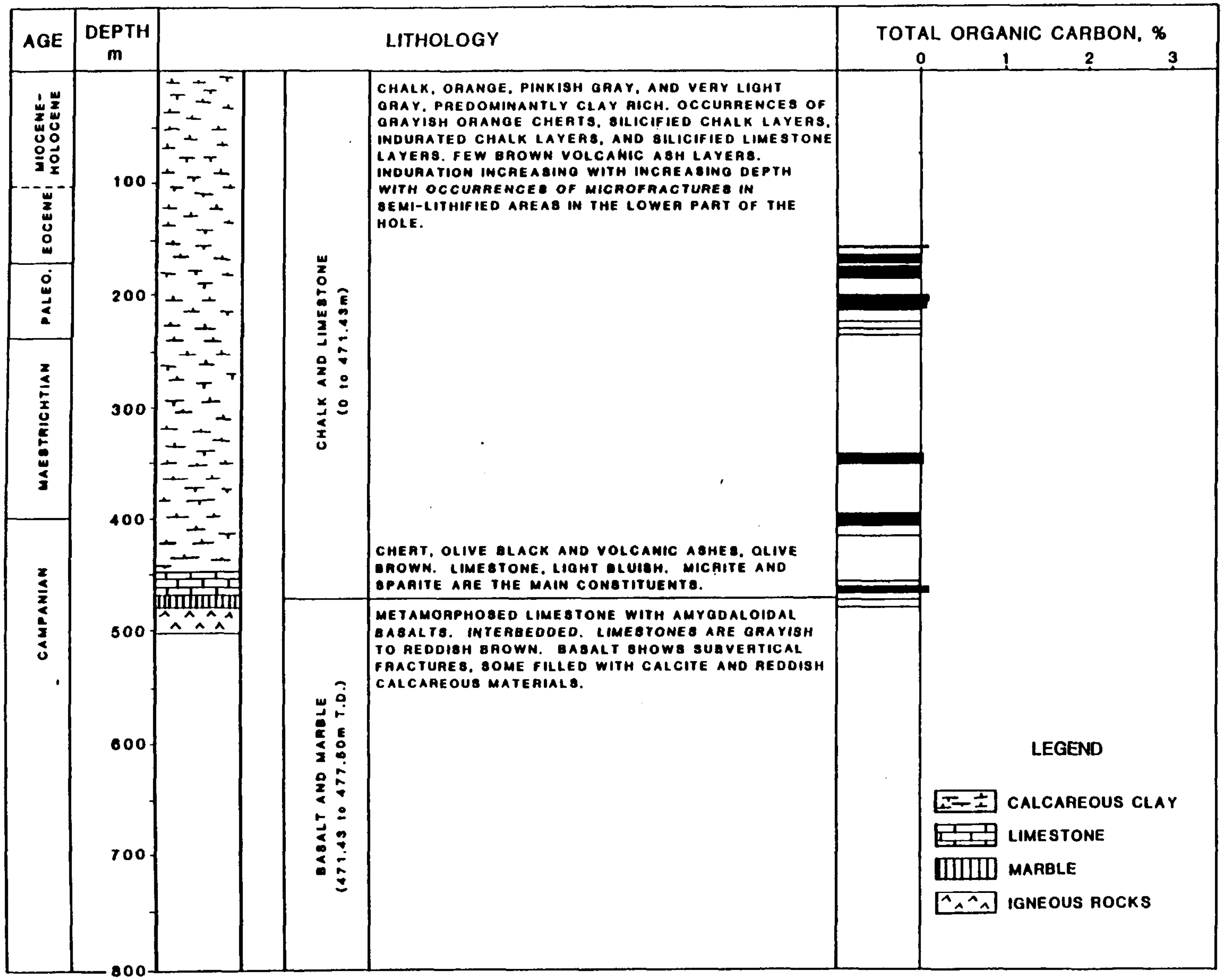


Figure 7. LITHOLOGY AND ORGANIC CARBON CONTENT, DSDP SITE 152

After Edgar et al., 1973

Gas-producing potential of the sediment is minimal. TOC values range from 0 to 0.2 with a mean of 0.02% (Figure 7; Bode, 1973). Of the 44 samples analysed from Site 152, 77% had TOC values below the limit of determination of the LECO furnace method. There was no mention of evolved gas in the site report (Edgar et al., 1973).

The basalt was vesicular with significant alteration present. The contact with the limestone was not recovered. However, marble was recovered above the basalt, and the basalt contained marble inclusions, suggesting that the basalt may be from a shallow sill/flow complex rather than being oceanic basement.

The consistently pelagic carbonate sediment cored at Site 152 does not provide much information on the timing of the development of the Nicaragua Rise. The interpretations derived from Site 151 are neither corroborated nor contradicted by the results of Site 152. The possibility that sediments may underly the basalt at Site 152 suggests the distinct possibility of an underlying organic-rich layer resulting from Santonian anoxia or pre-uplift deposition like that cored at Site 151. It is more likely, however, that this particular location has been in a bathymetrically high position since at least Campanian time, as not a single turbidite layer was cored. Prell (1978) has shown that Pleistocene turbidites are widespread in the adjacent abyssal plain.

Site 153 was located about 150 km southeast of Site 151 and 180 km north-northwest of the Guajira Peninsula of northeast Colombia (Figure 1). The site is on the far south flank of the Beata Ridge in the Aruba Gap, which separates the Beata Ridge and Colombia coast (Figure 8). The hole was drilled beneath 3,932 m of sea water, bottoming in basalt at 776 m. Upper sediments were clay-rich, becoming more calcareous with depth. Bands of carbonaceous material were found beneath 667 m (Figure 9.)

Site 153 was located to present an opportunity to sample sediments beneath a widespread Caribbean seismic reflector (B") which previous drilling had demonstrated to correspond to Cretaceous basalt (Edgar et al., 1973). Multichannel seismic sections of the Aruba Gap released to the DSDP scientists by Esso Production Research Company clearly showed layered reflectors beneath the B" horizon (Figure 10; Hopkins, 1973). Additionally, the seismic velocity of rocks beneath the B" reflector in the Aruba Gap is too low to be oceanic basement. The well indurated rocks in the lower reaches of the hole at Site 153 slowed drilling to the extent that the hole had to be abandoned without drilling through the Coniacian basalt correlative with reflector B" and sampling the subreflector sediments.

The shallowest cored intervals at Site 153 (102 - 309 m) are principally composed of middle Miocene to middle Pliocene calcareous clay. The lack of a major carbonate component in these cores is a reflection of the proximity of the site to the South American continent and the deposition of sediment near or below the carbonate compensation depth. With so little carbonate accumulation, terrestrial organic matter content of the sediment is significantly higher than in the marls and chalks of the Beata Ridge and Nicaragua Rise, with a mean TOC of 0.24% (Bode, 1973). As the seismic profile of the Aruba Gap (Figure 8) shows, a topographic high separates Site 153 from the South American continental margin and has prevented the accumulation of turbidites from the continental margin at the drilling site.

A 200 m thick more carbonate-rich unit of middle Oligocene to middle Miocene age with correspondingly lower TOC values mark a downward

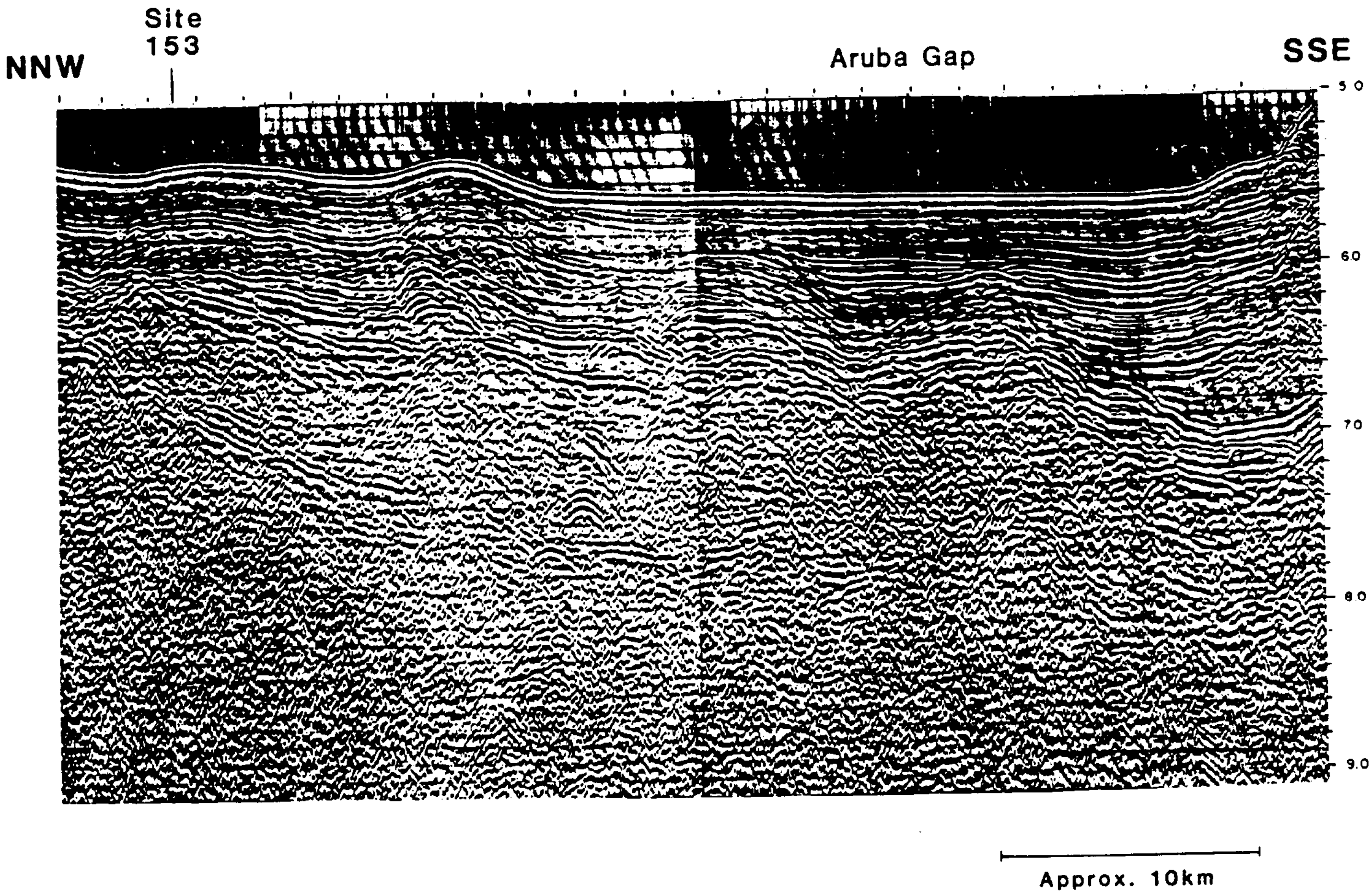


Figure 8. SEISMIC PROFILE B-2, ARUBA GAP, SHOWING LOCATION OF DSDP SITE 153

After Hopkins, 1973

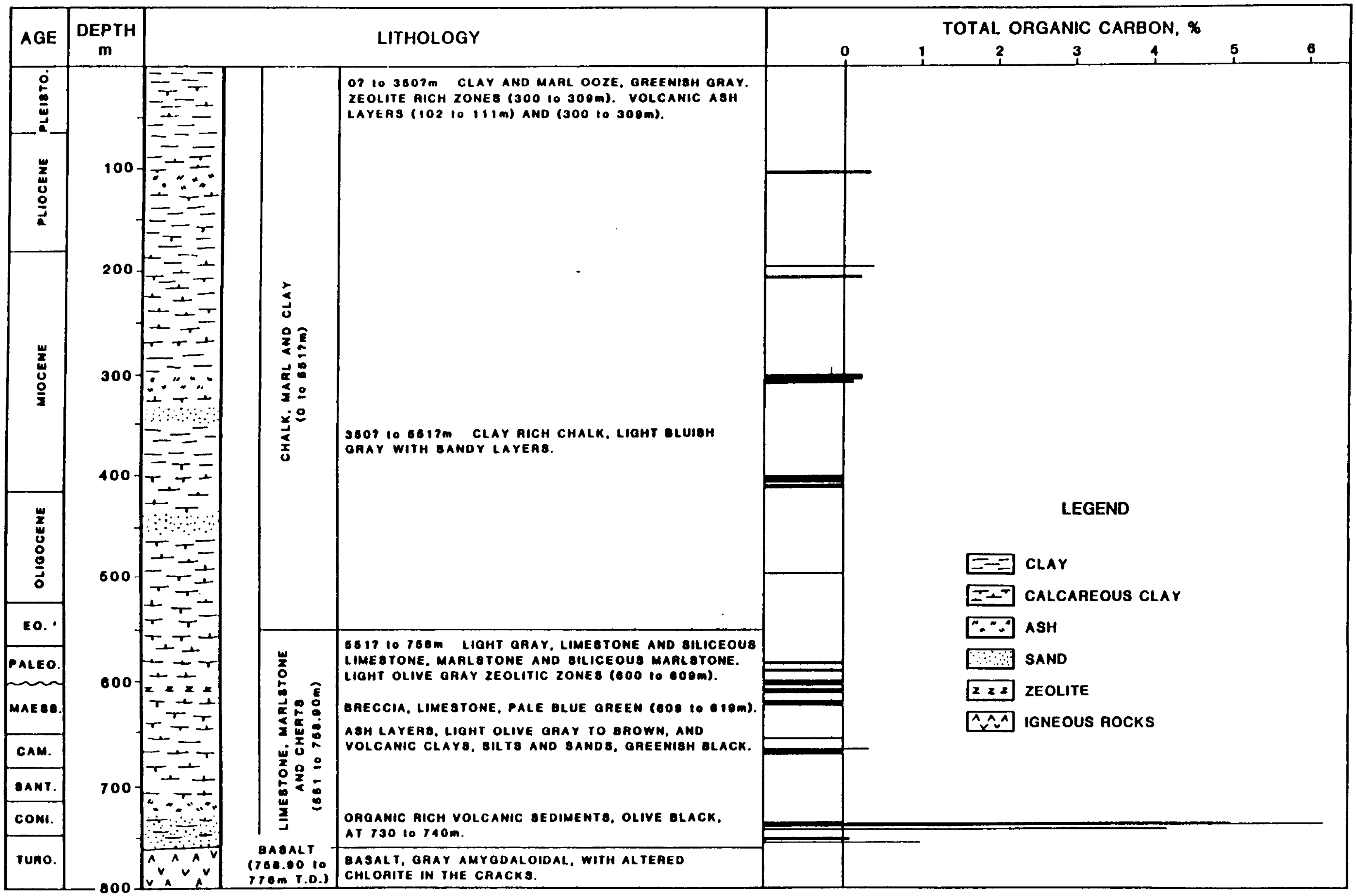


Figure 9. LITHOLOGY AND ORGANIC CARBON CONTENT, DSDP SITE 153

After Edgar et al., 1973

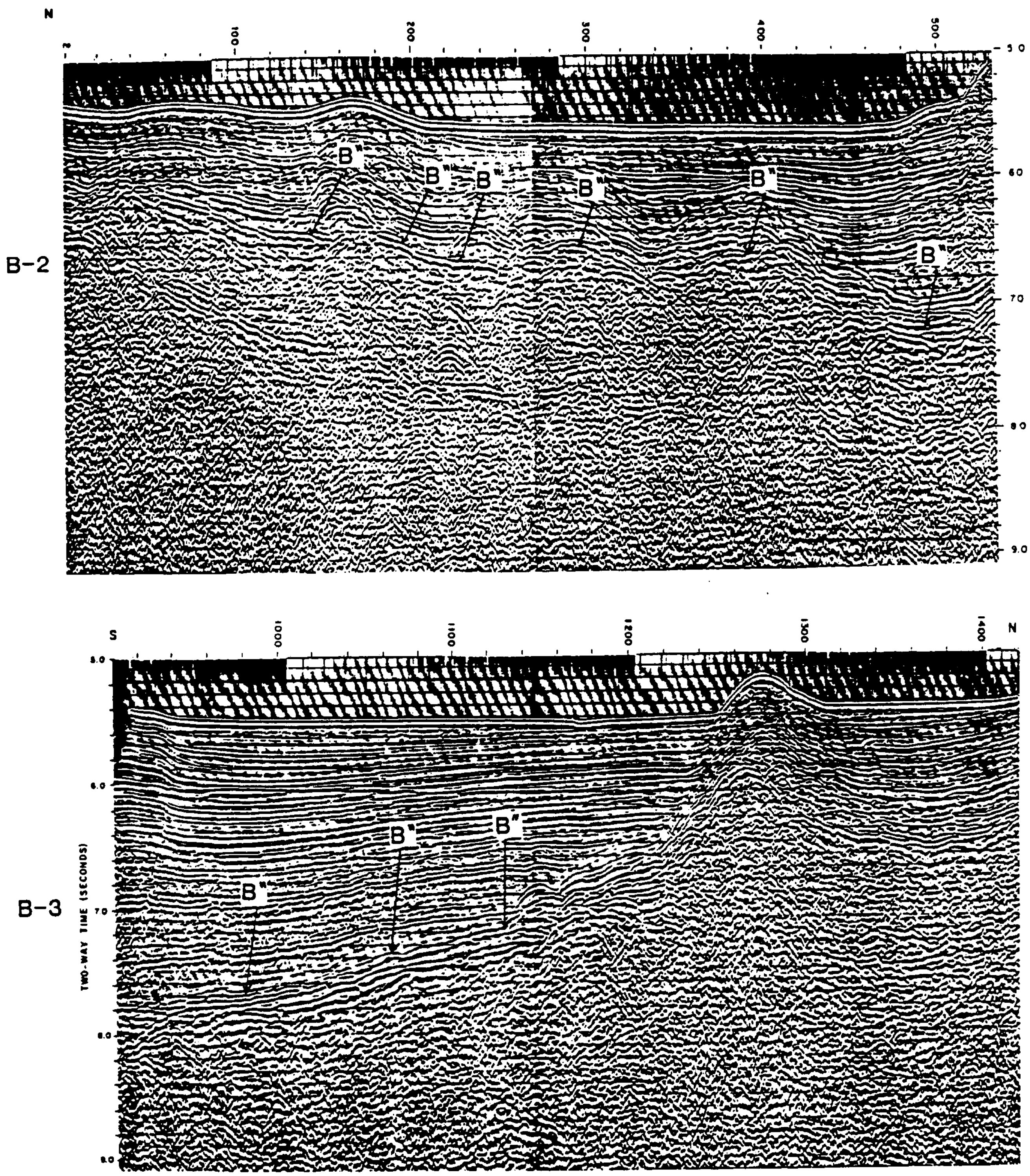


Figure 10. SEISMIC SECTIONS FROM ARUBA GAP SHOWING POSSIBLE SEDIMENTARY REFLECTORS BELOW B"

After Hopkins, 1973

transition to lower terrestrial input or shallower deposition. The TOC content of the tested samples of these intervals was consistently below the level of determination of the analytical method (Figure 9; Bode, 1973). Carbonate content of the sediment increased with depth from 30% to >90% (Edgar et al., 1973).

A drop in the drilling rate at 555 m represented a change from loose sediments to well indurated cherty limestones. Coring of this interval was begun at 563 m where a siliceous limestone of early Eocene age was obtained. Marls and argillaceous limestones to middle Paleocene age with no measurable organic carbon content make up this 60 m unit.

Silicified limestone breccia marked an unconformity spanning the Cretaceous-Tertiary boundary similar to the unconformity found at Site 151. Although the time gap represented by this unconformity is from middle Maestrichtian to middle Paleocene at Site 153 as opposed to late Santonian to early Paleocene at Site 151, Edgar et al. (1973) interpreted it to represent a parallel time of shoaling and exposure to stronger bottom currents which stripped unconsolidated sediments to the level at which silicic cementation prevented further erosion.

The pre-unconformity sediments are made up of interbedded limestones and clastics with some layers which are very rich in organic matter. Immediately beneath the unconformity at 610 m is a Maestrichtian argillaceous limestone or marl unit 60 m thick with varying numbers of chert nodules. Clay and phosphate interbeds in the limestone become more pronounced with depth. At 730 - 760 m, clastics become the principal lithology with volcanic sands, silts and ash layers predominating. Numerous layers rich in preserved organic matter are intercalated among the volcanic debris. Fish skeletons and discrete layers of unidentified organic matter are mentioned in the core descriptions (Edgar et al., 1973). TOC values as high as 6.9% were obtained on samples of these sediments (Bode, 1973; Figure 8). The TOC profile on Figure 9 illustrates that the sediments through this interval (730 - 740 m) are in discrete layers of diverse lithologies with correspondingly variable organic matter contents. Ash increases in occurrence toward the contact with the Turonian basalt in which the hole bottomed at 776 m. The shipboard party concluded that these organic-rich layers indicate ". . . the presence of a topographically diverse sea floor, with stagnant low areas in which fish debris and other organic matter accumulated with incomplete decomposition" (Edgar et al., 1973, p. 376). The concurrence of the carbonaceous layers with basaltic ash was interpreted as suggesting that the formation of the requisite topographic relief may have accompanied widespread basaltic volcanism in the area (Edgar et al., 1973).

Site 154 was drilled in the southwestern part of the Colombia Basin about 200 km north of the Panama Canal (Figure 1). The location chosen for coring was on a north trending faulted ridge 100 m above the general elevation of the surrounding basin (Figure 11). A distinct reflector at 0.2 sec subbottom on the seismic profile of the site in Figure 11 had been traced into the thick section of basinal turbidites adjacent to the uplift. By coring on the ridge, the thickness of sediment to be drilled to reach the depth of the distinct reflector was minimized. Also, being above the level of turbidity currents, the sediment drilled on the ridge would consist of easily datable pelagic sediments rather than potentially difficult-to-date resedimented deposits.

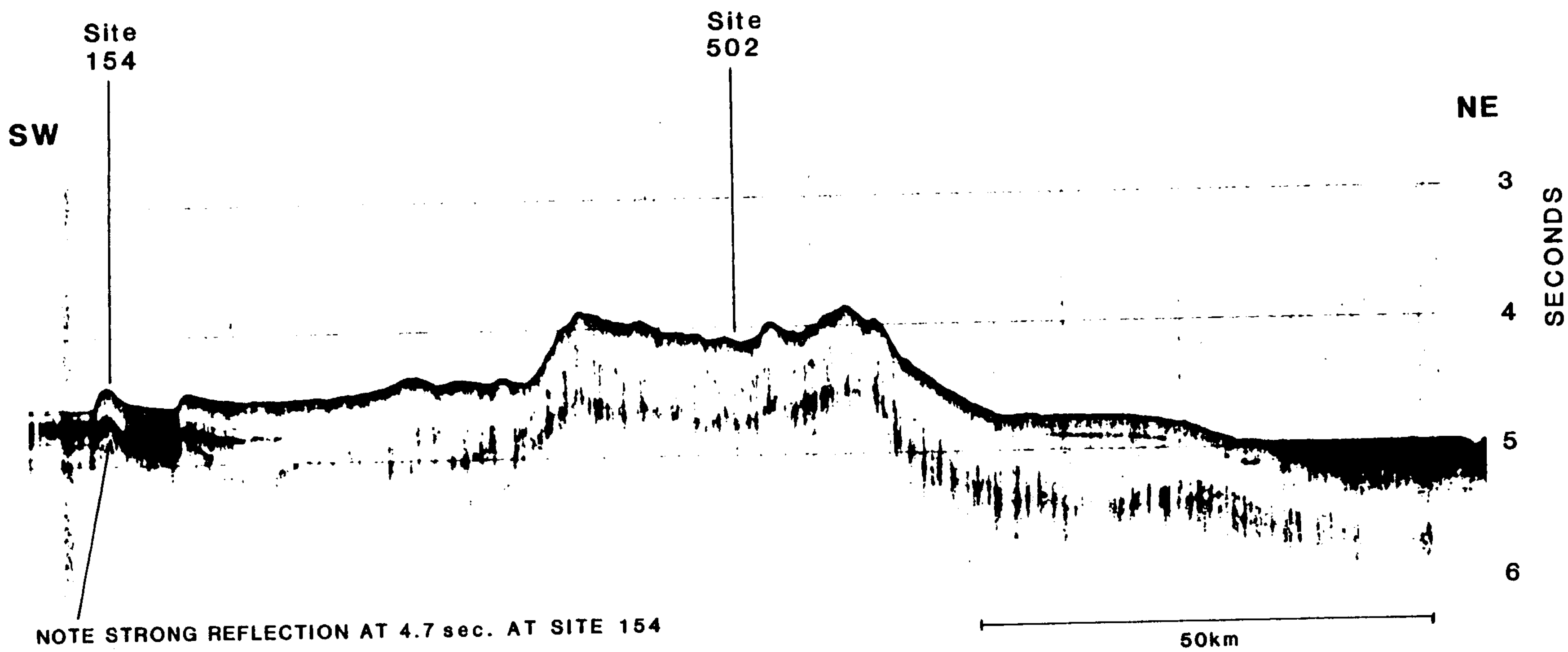


Figure 11. SEISMIC PROFILE SHOWING LOCATION OF DSDP SITES 154 AND 502

After Edgar et al., 1973 and Prell et al., 1982

Two holes were drilled at Site 154; one cored continuously from 164 to 277 m and the other cored continuously from the surface to 172 m, for a complete recovery of section at Site 154 (Figure 12). Two distinct units make up the penetrated sedimentary section, an upper pelagic marl unit and a lower terrigenous volcanic assemblage. The age of the contact between the units is interpreted to be early Pliocene.

The upper unit is composed of clay and biogenic carbonate debris. The pelagic sequence varies from calcareous clay to a marl in composition. Volcanic ash was found but not in large amounts as in previous holes. The organic content of the pelagic sequence, averaging 0.2%, is higher than similar deposits on Beata Ridge or the Nicaragua Rise (Bode, 1973). This is possibly due to the proximity to terrestrial sources and less local relief at Site 154.

The underlying coarse terrigenous unit contrasts sharply with the pelagic unit. The lower unit (153 - 280 m) is dominated by volcanic sands, silts, and clays (Figure 12). The depositional regime was clearly that of turbiditic-hemipelagic sedimentation from abundant calc-alkalic detritus. The volcanic section is most noteworthy for the abundant organic matter found in some samples (Bode, 1973; Figure 12). Well preserved wood fragments and terrestrial plant materials were described from the cores. Once again, it is evident from the range of TOC values throughout the lower section (0 - 5.9% TOC) that the carbonaceous material is localized in thin interbeds rather than being distributed evenly throughout the cores. This is consistent with the episodic nature of the basin floor sedimentation mechanisms dominant in the Miocene and early Pliocene.

Site 154 presents the strongest evidence yet for the possibility of abundant gas hydrates throughout the Colombia Basin. All cores recovered were gassy. Gas voids are recorded in core descriptions and core photographs. All cores are disturbed to varying degrees, as would be expected from exsolving gas in the sediments. There is no mention of specific core degassing properties which are now recognized as characteristic of dissociating gas hydrates. The site report (Edgar et al., 1973) mentions that the hole was discontinued at such a shallow depth due in part to "presence of hydrocarbons."

The dual nature of the sedimentary section was interpreted to again reflect the elevation of the drilling site above the general basinal level by tectonism. The uplift of this minor faulted ridge considerably postdates the inferred movement of the Nicaragua Ridge or the Beata Ridge. It also suggests that the bottom conditions which produced the Cretaceous and Paleocene organic-rich deposits elsewhere in the Caribbean were also present in the Colombia Basin as recently as the early Pliocene.

Site 502. A location in the western Colombia was selected as Site 502 of Leg 68 of the DSDP. The objective of Leg 68 was to use the newly developed hydraulic piston coring device to recover complete Neogene pelagic sections for comparison with sediments from nearby sites collected by conventional rotary coring (Prell et al., 1982). The hydraulic piston coring device was designed to allow collection of nonindurated sediments without the core disturbance that plagued rotary cored samples. The device preserves fine-scale stratification and sedimentary structures which had previously been obliterated upon recovery of rotary cores.

Site 502 was located 112 km east-northeast of Site 154 beneath 3,051 m of water (Figure 1). The drilling location was similarly situated on a ridge

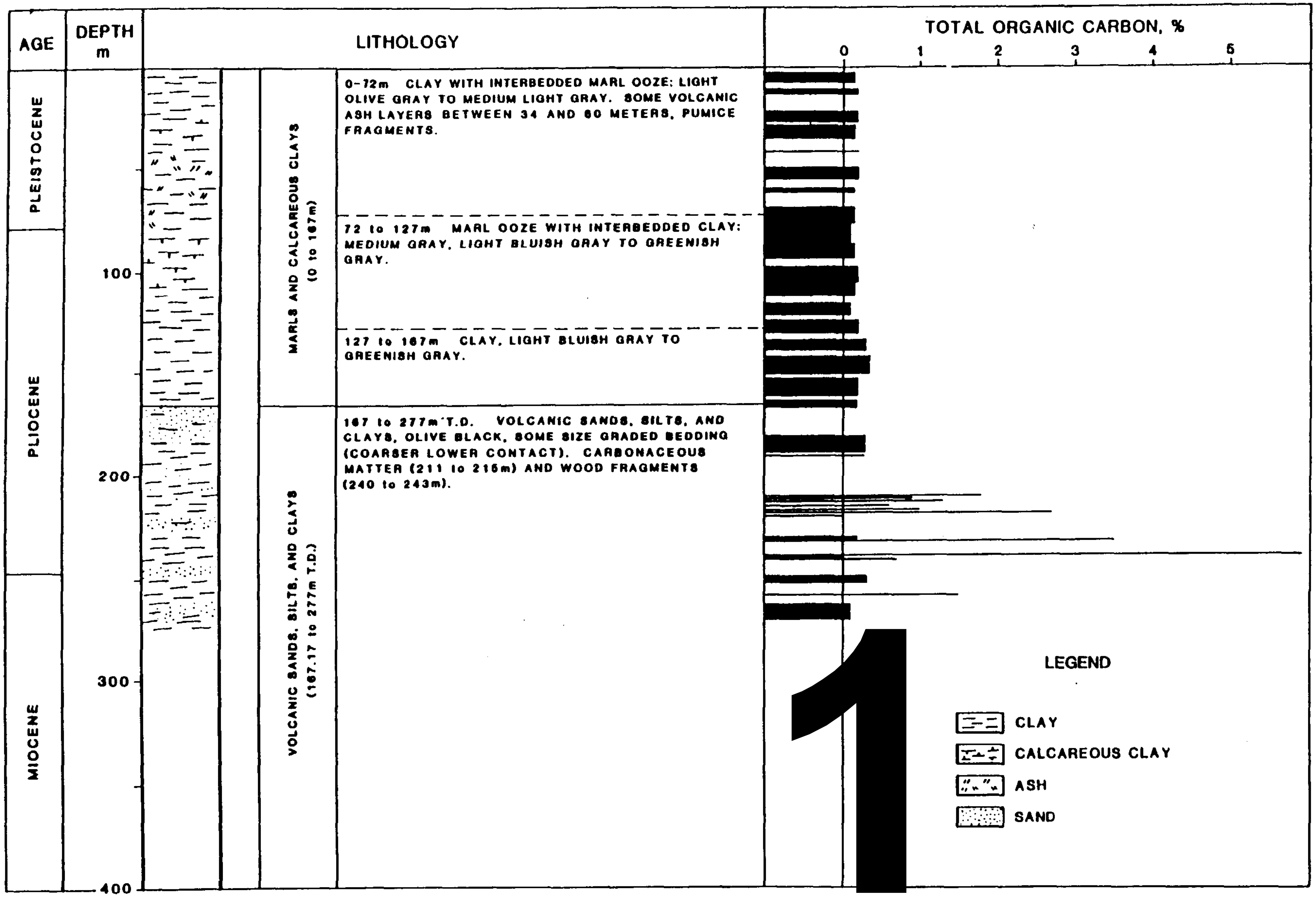


Figure 12. LITHOLOGY AND ORGANIC CARBON CONTENT, DSDP SITE 154

After Edgar et al., 1973

above the level of the surrounding basin to permit recovery of pelagic sediments rather than basinal turbidites. A comparison of the locations of Sites 154 and 502 reveals that Site 502 was drilled on a much larger and more elevated uplift (Figure 11). The distinct reflector at 0.2 sec at Site 154, which drilling showed to represent a Miocene-Pliocene volcanic turbidite unit, is absent at Site 154.

A pelagic-hemipelagic sequence was cored to 220 m subbottom (Prell et al., 1982). The sediments were composed of calcareous muds with varying amounts of clay above 220 - 210 m. Below this depth, Miocene volcanic clays and silts were recovered. However, these volcanic materials were apparently the product of direct hemipelagic sedimentation unlike the volcanic turbidites of Site 154. The volcanic hemipelagic sediment at Site 502 was interpreted by Zimmerman (1982) as being deposited slightly above the level of turbidity currents, but within the nepheloid layer of suspended clays associated with turbidity flows. The change of sediment type was dated at middle Miocene, indicating earlier uplift of the ridge than the early Pliocene movement assumed at Site 154.

Zimmerman (1982) also postulated that an unrecognized unconformity may have been penetrated at Site 154. Thus the fine-grained hemipelagic volcanic section cored at Site 502 may be a transitioal unit between turbidites and carbonate-clay pelagic sequences. A disconformity in the section cored at Site 154 between the pelagic ooze and the organic-rich volcanic turbidite units could reconcile the temporal and lithologic differences between the cored sections of Sites 154 and 502.

The lack of core disruption of samples recovered from Site 502 permitted more precise studies of the provenance of the Colombia Basin sediments. Analysis by X-ray diffractometry established that a transition in the character of terrigenous sediments at Site 502 occurred in the Pliocene. The deepest sediments cored have characteristics which indicate that weathered calc-alkalic volcanic rocks from Central America are the principal sediment source: abundant non-crystalline smectite, low illite/smectite ratio, a low quartz/feldspar ratio. Upwards in the hole, a smooth transition to factors which indicate a continental/metamorphic source terrane occur: high quartz/feldspar ratios; abundant amphibole, chlorite, and kaolinite; and rare smectite. These changes were apparent in a sediment column in which qualitatively similar direct hemipelagic sedimentary regimes were in effect. Zimmerman proposed that this transition in sediment type reflected a major change in oceanic circulation concurrent with the raising of the Panamanian Isthmus. Strong east to west currents through the Caribbean in the early and middle Tertiary, transferring water from the Atlantic Ocean to the Pacific Ocean, had been discussed by Holcombe and Moore (1977). Zimmerman (1982) stated that such currents would have prevented continental sediments from the Magdalena River from reaching Site 502. Only volcanic detritus from the Nicaragua/Costa Rica area could have been deposited on the topographically high area cored. The shoaling and eventual emergence of the isthmus would have stopped the strong westward circulation and the current pattern would have assumed a configuration similar to that at present.

Without a current barrier, the volumetrically more abundant continental sediments from the Magdalena drainage area could accumulate in the Colombia Basin. This scenario meshes well with the increase in sediment influx from the Magdalena River during the closure of the Panamanian seaway attributed by Kolla et al. (1984) to a major Pliocene orogenic pulse in the northern Andes.

No reports were made of gas associated with sediments at Site 502. No gas expansion voids were noted in core descriptions or photographs. The sediments were higher overall in mean organic carbon contents (0.41 vs 0.15) but apparently much less gas is being produced at Site 502 from Pliocene-Pleistocene sediments which are otherwise very similar to those at Site 154 (Gardner, 1980; Bode, 1973). It is possible that the gas reported in the pelagic units of Site 154 was not generated in these sediments, but migrated from the deeper volcanic turbidites.

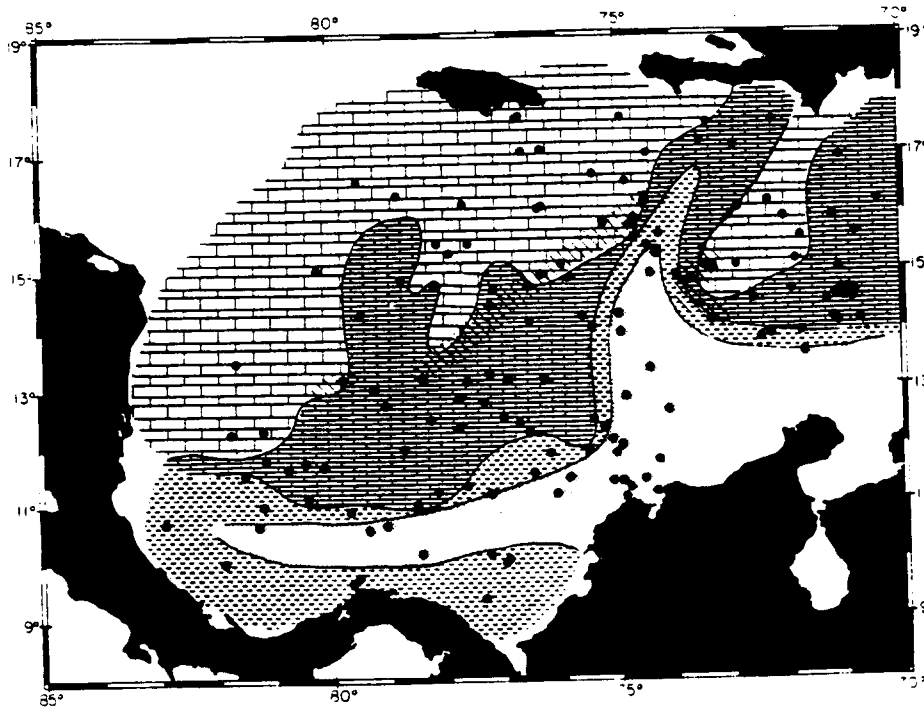
Shallow Cores

Many cores of Quaternary sediments of the Colombia Basin have been recovered by workers from Lamont-Doherty Geological Observatory (LDGO). These shallow cores (<3 m) have good areal coverage and include a wide variety of physiographic provinces in the study region. Prell (1978) presented a study of the temporal and spatial distribution of sediments in the Colombia Basin using lithologic and paleontologic data from these LDGO cores.

Prell classified the Holocene sediments of the Colombia Basin using the classification system of Olausson (1960), based on the content of $CaCO_3$ in the sediment. Sediments with more than 60% $CaCO_3$ are classified as ooze, 30% - 60% $CaCO_3$ constitutes marl, calcareous clay contains 10 - 30% $CaCO_3$, and sediments with less than 10% $CaCO_3$ are termed clay. The distribution of Holocene sediments so classified are presented in Figure K. The sediment distribution illustrates the expected terrigenous to pelagic transition from the Magdalena Delta basinward. The distinct geologic provinces previously outlined are also reflected in their basic Holocene sediment type. The Nicaragua Rise and Beata Ridge are prominently expressed as the only areas covered with principally calcareous ooze. The deep abyssal plains of the Colombia Basin are covered with marl. Clay and calcareous clay outline the general morphology of the Magdalena Fan, Aruba Gap, and the Panama and South Caribbean deformed belts.

Prell (1978) mapped the areal distribution of cores with recognizable turbidites in the upper Pleistocene section. His map, reproduced here as Figure 13, shows that essentially all of the deep plains of the Colombia Basin have been effected by turbidity currents during the Pleistocene. Most appear to be derived from the Magdalena delta. It is likely that those turbidites west of about 79° are derived from rivers in western Panama and Costa Rica. This concurs with the physiographic differentiation of this area by Case et al. (1984), and Holcombe's (1977) contention of west to east downslope sediment transport from the abyssal plain north of Panama to the abyssal plain north of Colombia. The turbidites cored near Hispanola at the far northeastern extent of the basin could be derived from the poorly defined Southern Haitian Borderland. Prell cautioned that the extent of turbidites on the present sea floor is much less than indicated on Figure 14. The uppermost turbidite units in the mapped cores are sometimes under as much as 3 m of pelagic sediment.

Prell stated that the principal control on carbonate content of Holocene sediments in the Colombia Basin is terrigenous dilution. An area of carbonate dissolution is centered over the Magdalena Fan. The dissolution is apparently related to a very high organic material flux from both terrestrial organic matter input and very productive upwelling zone. However, the effect of this



BASIC SEDIMENT TYPES

CALCAREOUS OOZE	>60% $CaCO_3$	
MARL	30-60% $CaCO_3$	
CALCAREOUS CLAY	10-30% $CaCO_3$	
CLAY	<10% $CaCO_3$	

Figure 13. DISTRIBUTION OF QUATERNARY SEDIMENT TYPES IN COLOMBIA BASIN

After Prell, 1978

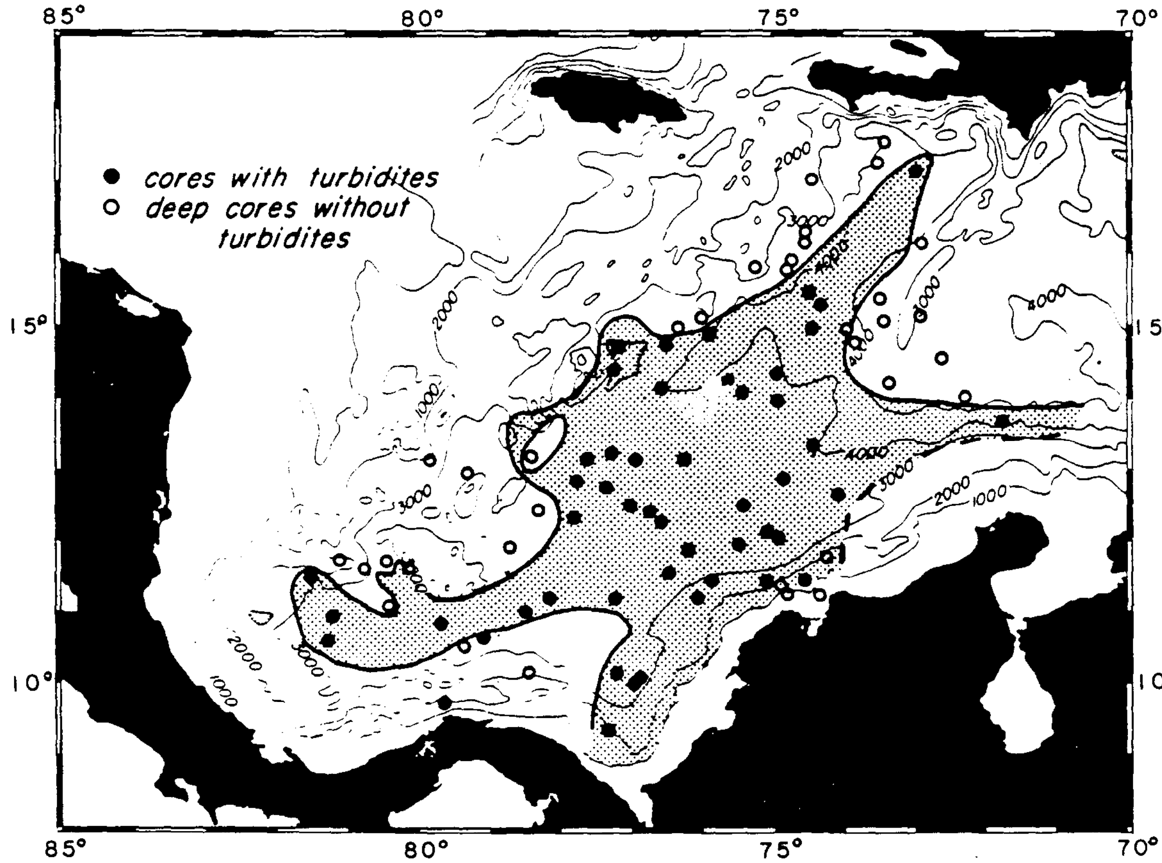


Figure 14. DISTRIBUTION OF UPPER PLEISTOCENE TURBIDITES IN THE COLOMBIA BASIN

After Prell, 1978

carbonate dissolution zone is limited to areas on and adjacent to the fan and does not greatly impact basinwide sedimentation. In other areas of the Colombia Basin, a consistent rain of carbonate material is diluted by a highly variable clastic supply. Thus, the ratio of carbonate to clastic sediments is a rough indicator of sedimentation rate; with a consistent background rain of carbonate sediment, an increasing clastic component fraction indicates a higher overall sedimentation rate.

Prell extended his findings from the Holocene to determine the sedimentological response to glacial eustatic sea level fluctuations in the Colombia Basin. Using cores which had been dated paleontologically and radiometricly, a consistent maximum in sediment carbonate content was noted in strata deposited 6,000 yr. B.P. A consistent minimum in sedimentary carbonate was recorded in sediments deposited 13,000 yr. B.P. Prell constructed lithofacies maps for the two time periods using only cores which experienced direct sedimentation during those periods (Figure 15). With 28 sample points rather than the 126 used in previous maps the contoured boundaries of these lithofacies maps are at places conjectural, but important general trends are evident. During the carbonate maximum at 6,000 yr. B.P., carbonate ooze extended basinward from the Nicaragua Rise and Beata Ridge somewhat more than in the Holocene case (Figure 13). Marl extended over broad areas of the basin 6,000 yr. ago, apparently covering large areas of the flat basin floor. Once again much of the area ascribed to marl deposition during this period has no control points; by extension it can be concluded that much of the marl region was indeed experiencing significant turbidite deposition at this time since all cores with turbidites had been removed from this data set. Calcareous clay is limited to a narrow zone offshore of western Panama. At the 6,000 yr. B.P. level, no clay type sediment (<10% $CaCO_3$) was cored throughout the basin.

The 13,000 yr. B.P. lithofacies map shows the encroachment of clastics into the pelagic domain during a major lowstand of sea level associated with a late Wisconsin glacial maximum. Clay sediment is widespread over the continental slope and rise. Most of the deep abyssal plains were covered by calcareous clay. Marl is restricted to the bordering bathymetric highs, the Nicaragua Rise and Beata Ridge. Deposition of carbonate ooze was practically nil during this period.

Since sedimentation rate is qualitatively proportional to clastic content of the sediment, sediment accumulation during sea level lowstands was substantially greater than at other times. This would probably be due to slope failures and gravity-induced wasting processes on the continental slope, and the greater sediment supply reaching the slope over the shelf.

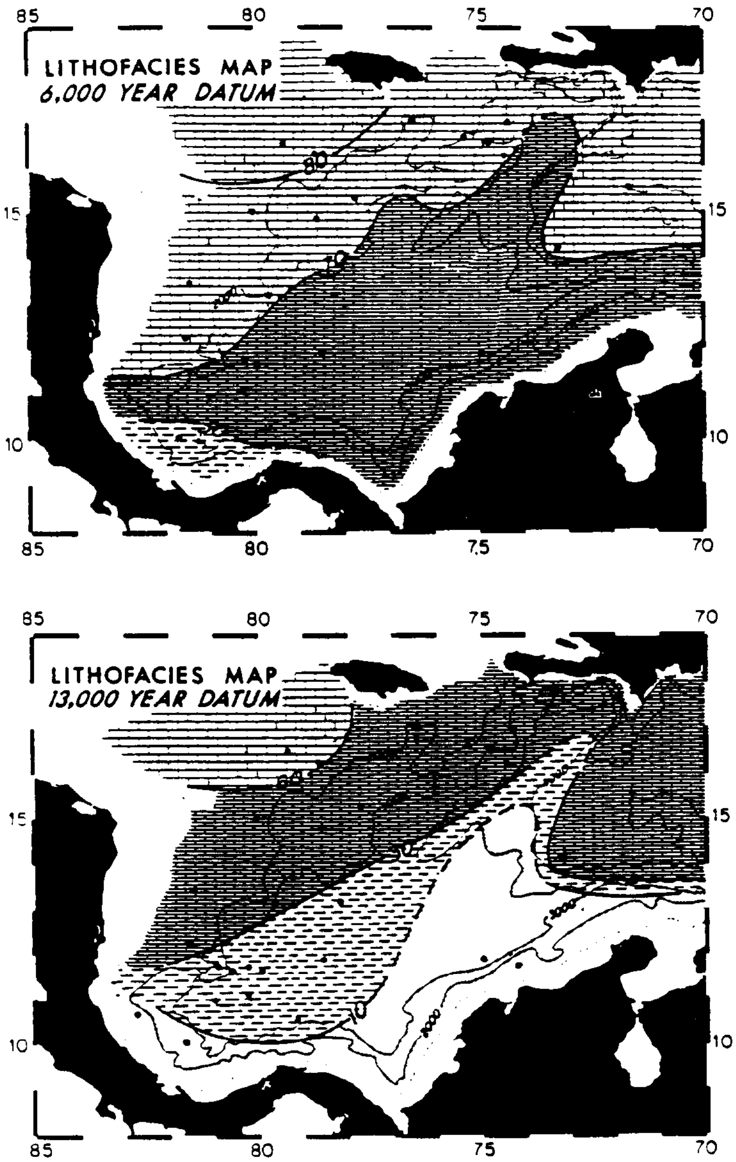
Five depositional environments were recognized in the 28 upper Pleistocene cores from the Colombia Basin. The characteristics used to define these environments are averaged over glacial and interglacial periods.

- Nicaragua Rise - characterized by consistently high carbonate (>60%), with up to 20% composed of foram tests. Accumulation rates average 2 - 3 cm/1,000 yr.

- Nicaragua Rise margin - lower in carbonate and coarse foram tests but with higher accumulation rates (4 - 5 cm/1,000 yr.). Deposits include slumps, carbonate turbidites, and distal terrigenous turbidites.

A

B



BASIC SEDIMENT TYPES

CALCAREOUS OOZE	>60% $CaCO_3$
MARL	30-60% $CaCO_3$
CALCAREOUS CLAY	10-30% $CaCO_3$
CLAY	<10% $CaCO_3$

Note: Sparse control in the southeast.
Contours in percent $CaCO_3$.

Figure 15. DISTRIBUTION OF SEDIMENT TYPES AT TIMES OF MINIMUM (A) AND MAXIMUM (B) TERRIGENOUS SEDIMENTATION

After Prell, 1978

- Beata Ridge - Cores have high but variable carbonate and foram test contents. Evidence of current winnowing and carbonate turbidites occur in these cores.

- Central Basin - Cores have an average $CaCO_3$ content of 30% with less than 10% foram tests. This environment is above the turbidite layer, but hemipelagic deposition is quite rapid, 4 - 5 cm/1,000 yr.

- Continental margin - Cores have low $CaCO_3$ content, few foram tests and exceedingly high accumulation rates, greater than 10 cm/1,000 yr.

Fox et al. (1970) reported dredging igneous rocks and sediments from the northwestern Beata Ridge. The recovered igneous rocks were principally diabase and holocrystalline basalt. A wide variety of minor igneous textures were encountered. Most sediment samples were pelagic foraminiferal carbonate oozes of Eocene to Pleistocene age. One sample recovered an Eocene carbonate pebble thought to represent a neritic depositional environment. The authors thus concluded that the Beata Ridge had foundered from a shallow depth, a hypothesis which was not borne out by DSDP drilling.

Seismic Stratigraphy

Seismic stratigraphic investigations have been important for interpreting the depositional style and probable sedimentary history of areas of the Colombia Basin which were not adequately cored. DSDP sites were intentionally located on deep topographic highs where slow pelagic sedimentation resulted in thin, easily dated sediment sections. The sedimentary makeup of large expanses of the basin floor and the Magdalena Fan has not been investigated by drilling. The DSDP holes which penetrated into sediments deposited prior to the uplift of the sites to their locally elevated positions recovered sediments with high organic carbon values, excellent organic matter preservation, and in one case abundant biogenic methane. Thus, the most prospective sediments for gas hydrate assessment, deep basinal Tertiary turbidites, are unsampled. Seismic stratigraphy permits analysis of the areal extent of seismic facies correlative with the untested sediments thought to have the greatest potential for gas hydrate development.

Single Channel Seismic Data

Two prominent reflectors were recognized on early single channel seismic reflection profiles of the Caribbean (Edgar et al., 1971). Seismic reflection surveys revealed a persistent deep reflector which corresponded with a sharp increase in seismic velocity as measured by seismic refraction. This deep reflector, termed B", was suspected of representing a sediment-basalt interface, but the measured seismic velocity of the rock beneath the reflector was significantly less than typical for oceanic basement. Additionally, faint reflectors beneath the B" reflector were seen on some profiles, further indicating that the B" reflector was not igneous basement. The reflector was unusually smooth in the Venezuela Basin, but showed much more local relief in the Colombia Basin.

A shallower, less persistent reflector, A", paralleled B". This reflector was correlated to middle Eocene cherts which were recovered by piston coring of a fault scarp (Talwani et al., 1966) and by deep sea drilling (Bader et al., 1970) in the Venezuela Basin. Subsequent drilling in the Caribbean (Edgar et al., 1973) showed that A" represents the transition from unconsolidated oozes to lithified sediments, generally marked by chert of middle Eocene age, but occasionally involving different rocks and ages from Paleocene to Miocene.

Recognition of these horizons in the southern Colombia Basin was limited by thick turbidites, however A" and B" could usually be seen dipping beneath the turbidite reflectors near the limits of turbidite deposition, implying that the turbidites were younger than A" (Edgar, 1971).

By extrapolation of a calculated sedimentation rate of 0.3 cm/1,000 yr., for post-A" pelagic sedimentation, Edgar et al. (1971) derived Early Cretaceous age for horizon B".

With denser control provided by a larger suite of single channel seismic data from various institutional sources, Holcombe (1977) mapped the areal extent of horizons A" and B". With this expanded data base, reflectors A" and/or B" could be mapped beneath most of the Colombia Basin. The reflectors were not visible under the Panama-Costa Rica Fan, the Magdalena Fan, or near the continental margin. Over the Beata Ridge the thickness of the A" to B" section diminishes and the A" horizon is restricted to small perched sedimentary prisms and the flanks of the ridge (Figure 16). Horizon A" can be found on most sections of the Nicaragua Rise, but horizon B" cannot be differentiated in the southwest portions of the rise (Figure 16).

Moore and Fahlquist (1976) presented stratigraphic and structural interpretations of the Aruba Gap, Beata Ridge, Colombia Basin abyssal plain, and Nicaragua Rise based on a single channel seismic line. The line was recorded from the deformed belt north of the Guajira Peninsula of Colombia 700 km northwestward to DSDP Sites 153, 151, and 152. The correlation of seismic reflectors with cored and dated sediments allowed the authors to hypothesize on the geologic history of the region. Horizon B" was traced all along the line, except beneath the Colombia Basin abyssal plain where highly reflective turbidites obliterate the reflector. No evidence of layered rocks beneath B" was found. Although the profile did cover the South Caribbean Deformed Belt, the quality of the data did not permit stratigraphic interpretation beyond concluding that the belt is composed of deformed sediment, and that the transition from the Aruba Gap to the deformed belt is covered by slump deposits. A turbidite wedge prograding northward over the Aruba Gap from the deformed belt was found to overly the typical Caribbean seismic sequence of two accoustically transparent layers (the "Carib Beds") separated by A" and floored by B". In the northwest cross-section, the Beata Ridge was seen to comprise two structural units, a southeastern unit of low relief fault blocks averaging 3,200 m sea floor depth, and an upper, rugged and steep section continuing northwestward toward the Colombia Basin abyssal plain. Horizon A", continuous across the Aruba Gap, disappeared midway across the southeastern Beata Ridge. The sediments between A" and B" thin before A" disappears, suggesting that contour currents may have stripped sediments down to basalt during or after uplift of the ridge. The sediments over the main segment of the ridge near DSDP Site 151 are transparent. The turbidite reflectors of the abyssal plain are underlain by a curious reflector at about 0.6 sec subbottom. This pervasive reflector overlies and masks the A" reflector in the basin. This reflector differs in both seismic response and stratigraphic position from the turbidites. Moore and Fahlquist (1976, p. 1614) suggested that the unusual reflector beneath the Colombia Basin abyssal plain may represent a diagenetic boundary or a gas hydrate zone. Reflectors A" and B" were evident across the Nicaragua Rise, with A" converging on B" over structural highs. It is unclear whether this is due to differences in sedimentation, or whether the A" reflector on the elevated blocks is an unconformity due to stripping of sediments by currents.

The Magdalena Delta and Fan have been the subjects of at least three published seismic studies. These studies have indicated that the continental margin offshore of the Rio Magdalena is composed of channeled turbidite and deltaic facies which cover the accretionary structures that characterize the margin elsewhere along the Caribbean coasts of Panama and Colombia.

Krause (1971) studied the bathymetry, structure, and sedimentation of the eastern portion of the Magdalena Delta and Fan, and the adjacent continental margin eastward to the Aruba Gap. His seismic data were limited to single channel air gun profiles. Although the survey was aimed principally at establishing a detailed bathymetric map of the area, some relevant information on the dominant depositional processes was established. The area offshore of Rio Magdalena is covered by channelized sedimentary layers covering previously formed folds. Some active folds which roughly

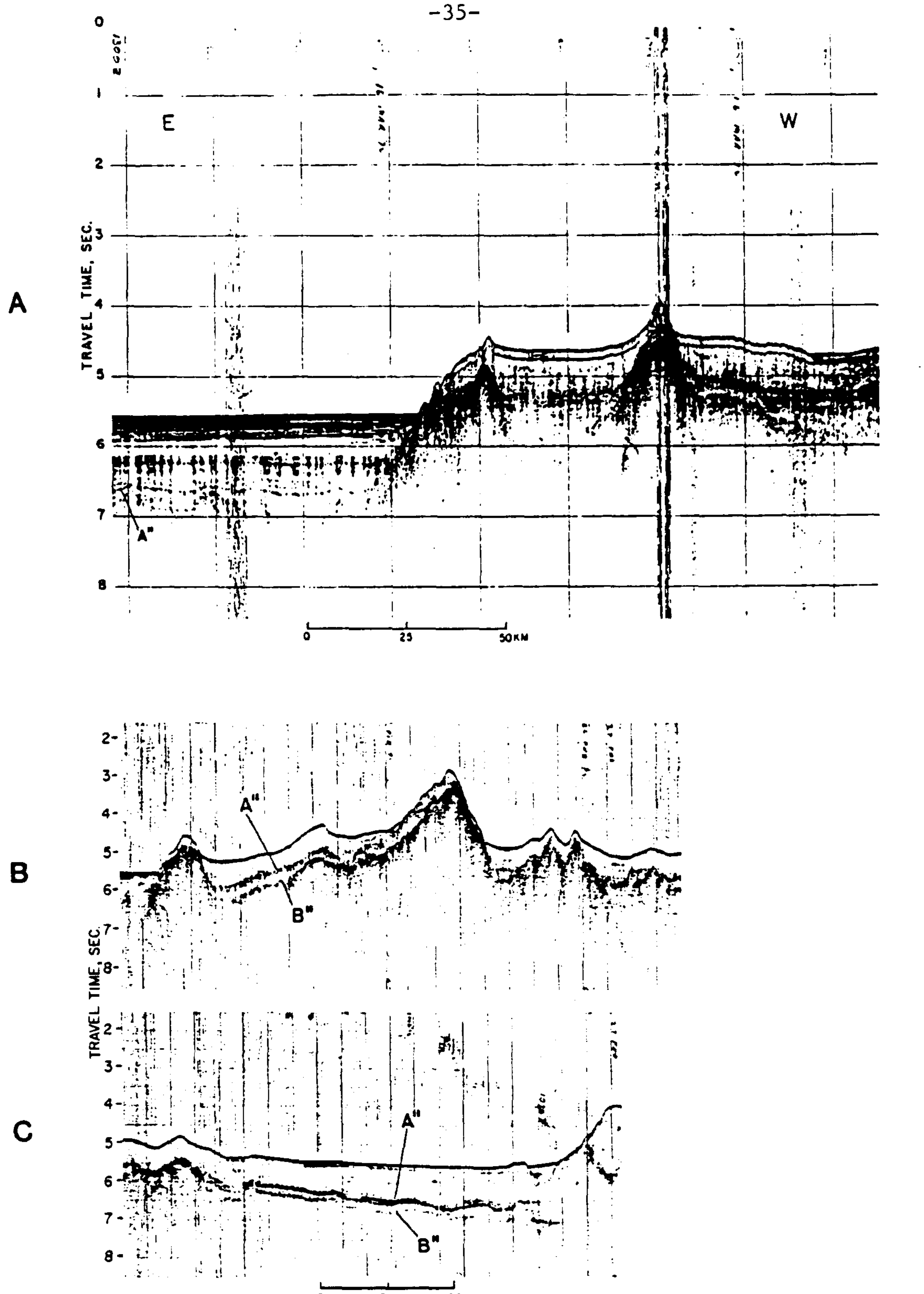


Figure 16. SEISMIC PROFILES OF THE NICARAGUA RISE (A) AND BEATA RIDGE (B AND C) SHOWING REFLECTORS A" AND B"

After Holcombe, 1977

parallel the coastline show that deformation is occuring contemporaneously with deposition leading to ponding of sediments beneath the folds.

Krause demonstrated that the Colombia continental margin is dissected by large canyons. One major canyon, Aguja Canyon is very deep (~500 m) and extends from the continental slope to within 5 km of the Colombia coast. The head of the canyon abuts the coast at Cabo de la Aguja, a promontory of the Sierra de Santa Marta range having a vertical relief of over 5,000 m. There are no major rivers anywhere near the head of the Aguja Canyon. Wide troughs of similar depth were found to drain into and out of a large forearc structure, the Rancheria Basin, but these canyons coincide with the probable Pleistocene course of the Rio Rancheria. Although the Rio Magdalena is widely assumed to be the major sediment source for the Colombia Basin, no large, distinct submarine canyon system emanating from the delta was found by Krause.

A seismic study of a smaller area centered on the Magdalena Delta and Fan was conducted by Shepard et al. (1968) and Shepard (1973). More closely spaced lines allowed Shepard to map the sediments and canyons of the delta more completely. One finding from this study is that the small canyons emanating from the Rio Magdalena are more contorted and irregular than previously believed. Shepard's work also confirmed that a large canyon exists west of the present mouth of Rio Magdalena, indicating that the river had a more westerly course in the past. Shepard chose to call these Magdalena canyons "slump valleys," indicating that their location and expression were largely controlled by slumping parallel to strike rather than downslope sediment scouring. Shepard found that the Aguja Canyon trended successively north then west, rather than linearly northwest as had been postulated by Krause (1971). Furthermore, it appears that the head of the canyon does not abut the Sierra Marta Massif, but trends eastward, paralleling the coast a few kilometers offshore. Shepard noted that the trend of the canyon head aligned with the Oca Fault, a major strike slip fault with prominent expression on land (Kellogg and Bonini, 1981). He found sedimentation to be largely structurally controlled, with active grabens and slump depressions being the sites of rapid sedimentation. Shepard also mapped mud diapirs in a northeast trending belt between the Rio Magdalena and the Aguja Canyon 30 to 50 km offshore.

Multichannel Seismic Data

The greater penetration and resolution of multichannel processed seismic data has allowed more detailed seismic stratigraphic studies of the Colombia Basin. A large number of multichannel seismic surveys have been performed in the western Caribbean due to the unusual structural features of the Colombia Basin and the proximity of the study region to the extremely productive petroleum provinces of Venezuela. However, very few of the resulting multichannel seismic lines have been released to the public. Two multichannel lines of the Aruba Gap compiled by Esso Production Research Company were published in a paper by Hopkins (1973). Three multichannel sections of the Colombia continental margin were released by Shell International Petroleum Mij. B.V. for inclusion in an article by Lehner et al. (1983). Lamont Doherty Geological Observatory (LDGO) collected a series of multichannel lines in the Caribbean. Three of these sections from the

Colombia continental margin were published by Ladd and Truchan (1983) and Ladd et al. (1984). An LDGO seismic section of the Magdalena Fan was included in a paper by Kolla et al. (1984). The University of Texas Institute for Geophysics (UTIG) has collected much multichannel seismic data in the Caribbean. Some of the surveys were conducted with industry funding and remain proprietary. However, some very informative UTIG lines have been published. Three seismic sections, one from the Panama Deformed Belt, one from the South Caribbean Deformed Belt, and one from the central basin, were included in a paper by Lu and McMillen (1983). The two continental margin seismic lines in this paper displayed very well developed BSRs and were the basis for designating the Colombia Basin as a gas hydrate study site by DOE-METC. A segment from another UTIG line from the Colombian continental margin and one from the Magdalena Fan were published in an article by Kolla et al. (1984). Another composite series of seismic lines stretching from the Panama Deformed Belt northward to the Nicaragua Rise have not yet been included in a journal publication, but are publicly available from UTIG (Figure 3). The location of the seismic lines mentioned in the text are shown in Figure 17.

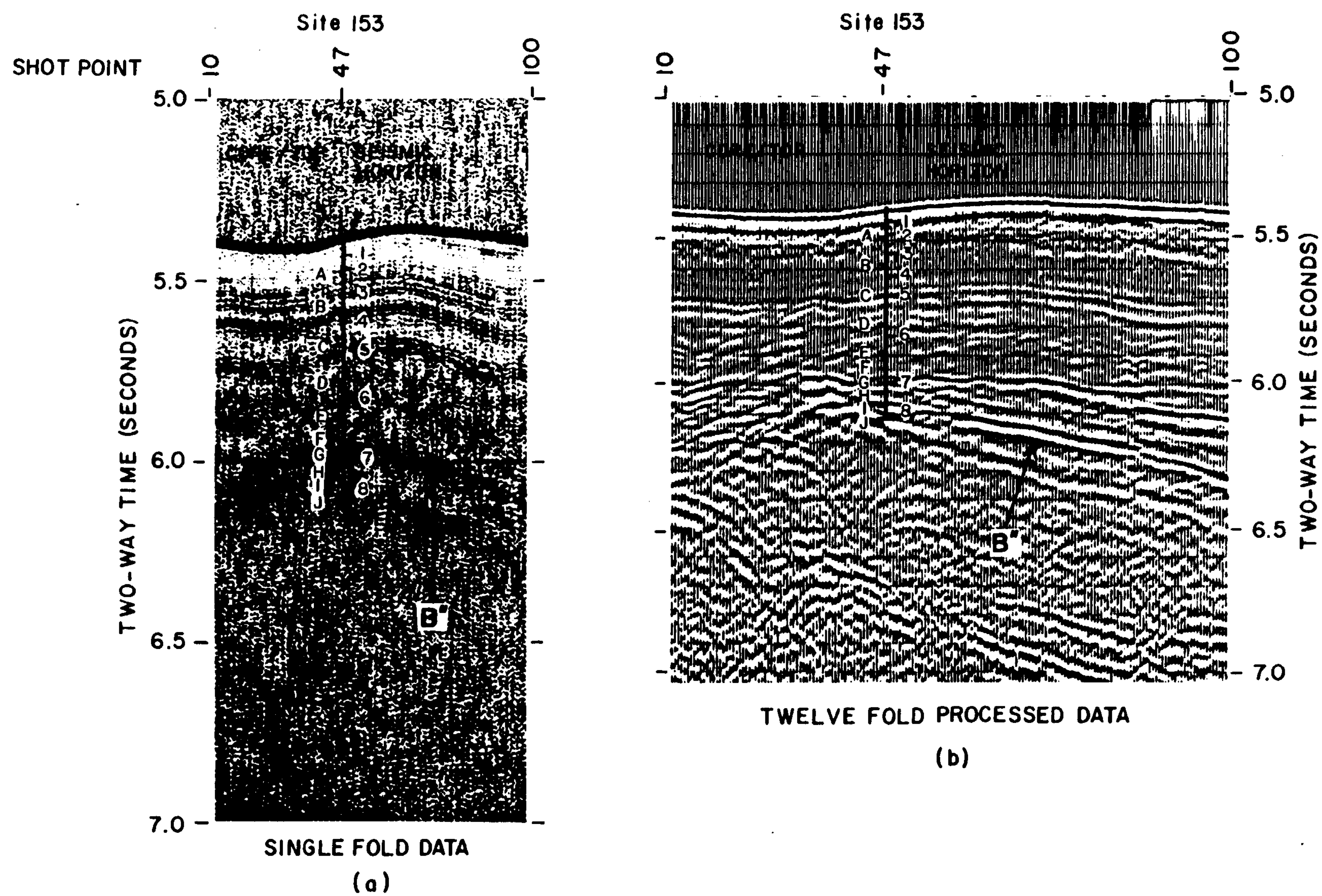
The Esso multichannel seismic lines from the Aruba Gap were provided to the DSDP staff scientists for use in the planning of drilling sites for Leg 15. Lines B-2 and B-3 clearly showed layered reflections beneath B" (Figure 10). The location for Site 153 was selected over an uplifted crustal block where B" was shallow enough that penetrating to sample sub-B" rocks was feasible. Due to time constraints, drilling at Site 153 was terminated before reaching sub-B" rocks. However, the penetration was sufficient to allow Hopkins (1973) to correlate seismic and lithologic units of the Aruba Gap (Figure 18, Table 2).

Although Hopkins' interpretation dealt mainly with the structural geology of the area, some stratigraphic inferences were also made. By correlating seismic response with bore hole information (Figure 18) Hopkins was able to provide probable depth/age relationships of strata of the Aruba gap. Figure 19 illustrates his interpretation of seismic horizons. The seismic section was divided into 9 seismic units. Unit 8 (reflector B"), a distinct high amplitude reflector coincided with the Coniacian basalt in which the hole at Site 153 bottomed.

Seismic unit 9 was the deepest coherent reflector present on the sections. The seismic velocity of the rocks below unit 9 measured 5,120 m/s, and Hopkins assigned that unit to represent oceanic basement. The interval between reflectors 8 and 9 (sub-B" interval) has a calculated seismic velocity of 3,870 m/s, midway between the velocities expected for oceanic sediments and for solid basalt. The sub-B" rocks above the true basaltic crust would thus appear to be composed of interbedded sediments and basalt to diabase flows or sills. The apparent thickness of the sub-B" unit varies from 600 m near the Beata Ridge to 2,300 m adjacent to the marginal deformed belt (Figure 19).

The reflector designated 7 by Hopkins corresponds with the cored Maestrichtian to Paleocene unconformity drilled at Site 153. Saunders et al. (1973) stated that reflector 7 is the same as A" in this section. Some disparity in interpretation exists in the reports by Hopkins and the shipboard scientific party concerning the correlation of reflector A". The shipboard scientists stated that A" corresponds to a downward transition from poorly

FIGURE 17, Seismic Track Lines in the Colombia Basin Study Region, is located in the pocket at the end of the report.



(a) SINGLE-FOLD DATA, AND (b) TWELVE-FOLD PROCESSED DATA OF THE SAME AREA. A THROUGH J ARE TOPS OF CORE INTERVALS OR GEOLOGIC CONTACTS KEYED TO CORE DESCRIPTIONS IN FIGURE . 1 THROUGH 8 ARE MAPPED SEISMIC HORIZONS. HORIZONTAL DISTANCE IS APPROXIMATELY 10km.

Figure 18. SEGMENT OF SEISMIC LINE B-2, ARUBA GAP SHOWING CORRELATION OF SEDIMENTS AND REFLECTORS

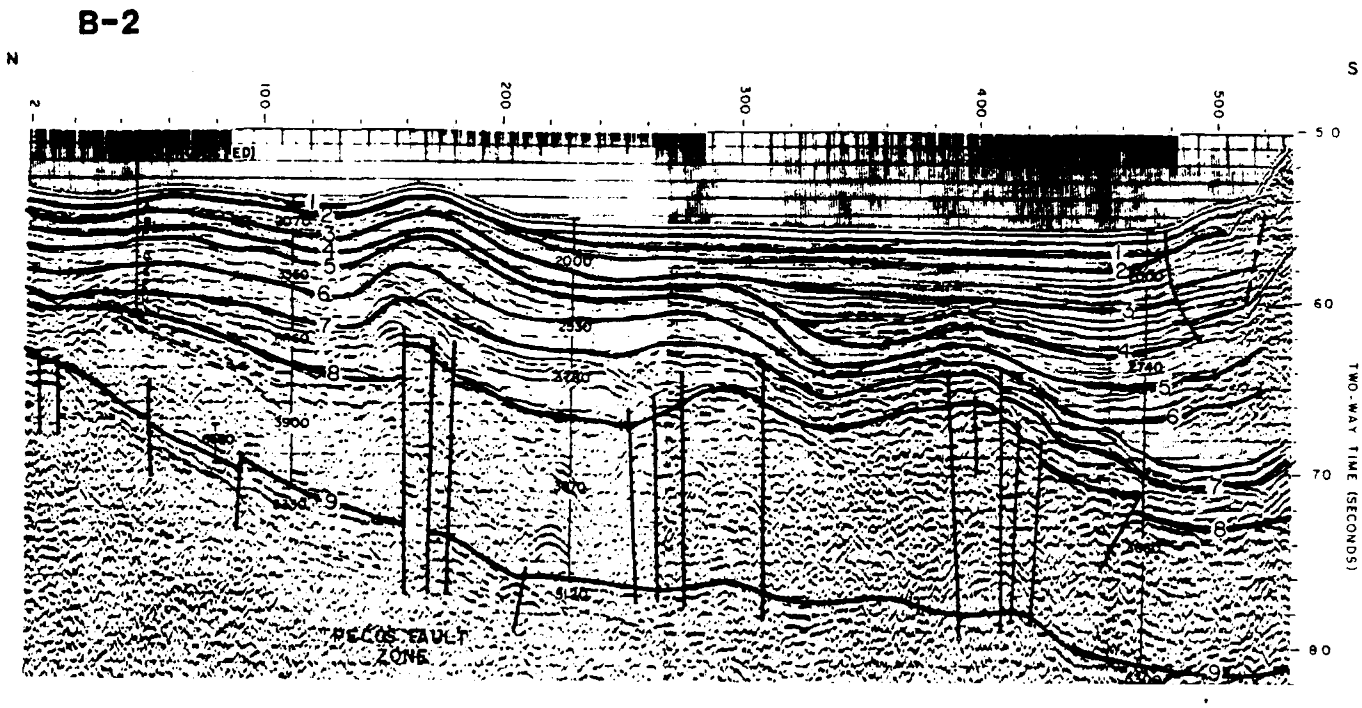
From Hopkins, 1973

TABLE 2.

CORRELATION OF DRILL HOLE DEPTHS AND SEISMIC HORIZONS, DSDP SITE 153. After Hopkins, 1973.

Drill Hole				Seismic Line		
Core/Tops	Age	Depth, m	Two-way time, sec*	Horizon	Depth*, m	Two-way time, sec
Water Bottom		3932	5.37	Water Bottom	3932	5.37
				1	3982	5.42
A	m. Pliocene	4034	5.47	2	4022	5.46
				3	4093	5.53
B	l. Miocene	4132	5.57			
				4	4173	5.61
C	m. Miocene	4232	5.67	5	4243	5.68
D	e. Miocene	4335	5.77			
				6	4384	5.82
E	m. Oligocene	4432	5.87			
F	e. Eocene	4495	5.93			
G	Maestrichtian	4541	5.98	7	4541	5.98
H	Santonian	4663	6.06			
J	Basalt	4691	6.09	8	4684	6.09
T.D.		4708	6.10			

* Seismic times in the drill hole and depths of the seismic horizons are based on calculated velocities. Water velocity is 1,463 m/sec; sediment velocity from 5.37 sec to 5.98 sec is 2,009 m/sec; and rock velocity below 5.98 sec is 2,528 m/sec.



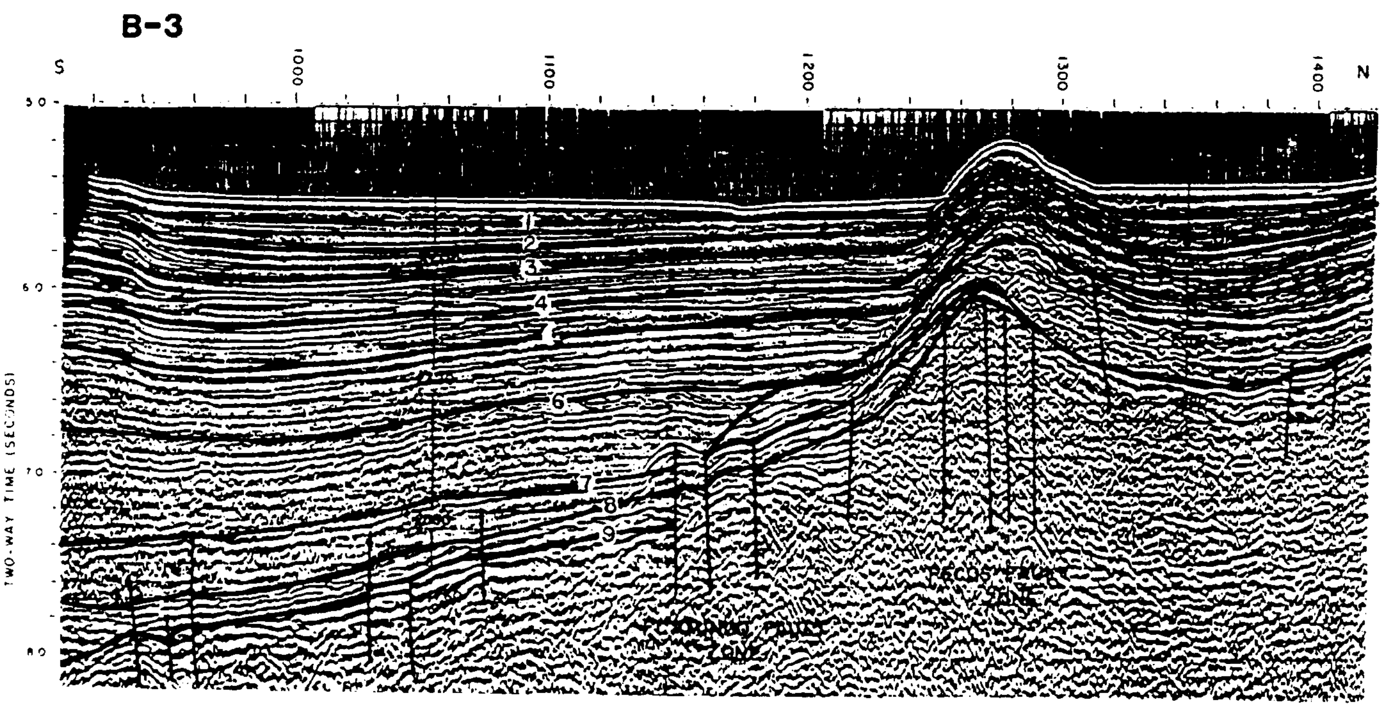


Figure 19. SEISMIC LINES B-2 AND B-3 AS INTERPRETED BY HOPKINS, 1973

consolidated Eocene-Holocene oozes to cherty, well lithified limestones of Maestrichtian to early Eocene age. Either interpretation is tenable; both transitions, from ooze to limestone, or from limestone to highly siliceous and brecciated limestone "hardground," should have seismic expression. The two cored horizons are about 60 m apart, which corresponds to 0.03 sec two way travel time. Which lithological boundary corresponds to the strong seismic reflector could be determined by looking for unconformable relationships along the horizon. Hopkins claims that his reflector 7 is a "conspicuous unconformity" and thus corresponds to the Cretaceous-Tertiary boundary cored at Site 153.

Organic-rich upper Cretaceous sediments are contained in the interval between horizons 7 and 8 (A" and B") at Site 153 (Bode, 1973). It is possible that the organic production and preservation which produced such TOC values (up to 6.2%) are expressions of local topographic and biologic conditions and cannot be extended basinwide. However, the recovery of Santonian organic-rich clays (up to 6.2%) at Site 151 on the Beata Ridge suggests that the Late Cretaceous may have been a time of widespread deposition and preservation of organic-rich sediments in the Caribbean.

The work of Hopkins allows us to trace the section of Upper Cretaceous possibly organic-rich sediments into the basin. The Cretaceous interval between reflectors 7 and 8 (A" and B") increases in thickness to the south, ranging from 0.1 sec at Site 153 to 0.4 sec 60 km south, averaging 0.2 sec (300 m) along the section from Site 153 to the thrust faults marking the boundary of the Aruba Gap and the South Caribbean Deformed Belt (Figure 19). The Cretaceous interval generally deepens southward in the section, but numerous faults and folds reflecting basement movement complicate this trend (Figure 19). The Cretaceous section has a mean depth of 0.8 sec (900 m) across most of the Aruba Gap on section B-2. The Cretaceous section dips toward the continental margin reaching a depth of 1.8 sec (2,200 m). On section B-3 from 20 km further west, Hopkins correlated seismic units and found that the unit 7 - 8 (A" and B") interval steadily increases in thickness, 0.1 to 0.3 sec (120 to 400 m), and depth, 1.0 to 2.1 sec (1,200 to 2,500 m), southward toward the continental margin. Section B-3 is substantially less faulted than section B-2 (Figure 19).

The above extensions of Hopkins' work indicates that the only lithologic interval which has been analytically determined to be rich in organic matter is generally too deep to be in the gas hydrate stability zone. BSRs from the adjacent continental margins on seismic lines 129, 130, and 1422 have average depths of 0.6 to 0.7 sec. Thus, the top of the potentially organic-rich Cretaceous sediments are in the BSR depth range over only 15% of the Aruba Gap in Section B-2 and over only 2% of portion of the Aruba Gap represented by section B-3. For the Cretaceous sediments to be the source for biogenic gas in hydrates in the Aruba Gap, substantial vertical migration would have had to occur, possibly through the fault zones annotated by Hopkins in Figure 19. Near the margin, the Cretaceous section is deep enough that incipient thermal maturation of kerogen may be possible, raising the question of possible thermogenic source of gas hydrate horizons in the adjacent continental margin.

Analysis by Bode (1973) showed that only sediments between seismic units 7 and 8 (reflectors A" and B") contained abundant organic carbon at Site 153. The shallowest recovered core, dated as Miocene to middle Pliocene had organic carbon values of 0 - 0.4%. The remainder of the Tertiary cores had negligible organic carbon. It is likely that as these barren or lean strata are traced into the basin (southward), the organic carbon content of sediments increases. Since the Paleocene, Site 153 has been subjected to dominantly pelagic and hemipelagic sedimentation. A ridge south of Site 153 has restricted turbidity flows originating from the continental margin from reaching the elevated location of Site 153. As sedimentary horizons are traced from Site 153 toward the continental margin, one would expect a change in sediment character to terrigenous turbidite deposits with, presumably, higher organic carbon content.

Lu and McMillen (1983) performed a detailed multichannel seismic stratigraphic and structural study of the southwestern part of the Colombia Basin region (west of 76° W). UTIG multichannel seismic lines from the CT1, CB, NR, and PN series were evaluated to establish depth of sediments, seismic facies, and the structural style of the marginal deformed belt and the abyssal areas.

Lu and McMillen recognized 4 seismic facies in the western Colombia Basin (Figure 20). Two facies types were restricted to topographically elevated structures within the basin. The marginal deformed belts (North Panama Deformed Belt and South Caribbean Deformed Belt) are characterized by strongly folded and faulted sediment wedges with a thin (0.10 sec) continuous sediment apron and lower laminated and chaotic reflectors. The resolution of sedimentary layers within the deformed belt facies varies between seismic lines; tilted turbidite reflectors and visible in some lines, chaotic reflections prevail in others.

Rise facies were encountered only on the Nicaragua Rise and minor topographic highs in the basin. In these sections, a thin (0.1 sec) double reflector at the sea floor is underlain by an acoustically transparent layer averaging 0.5 sec in thickness. Over the Nicaragua Rise the transparent layer is floored by what appears to be faulted igneous basement, with identifiable sediments visible only beneath small perched plains.

Basin floor type stratigraphic units were mapped over most of the abyssal plain of the western Colombia Basin (Panama Plain of Holcombe, 1977; Figure 20). The basin floor type stratigraphy comprises four seismic units separated by distinct reflectors (Figure 21). The uppermost unit (CBI1 on Figure 21) resembles a thin (0.3 sec) variation of the rise type stratigraphy with two or three strong sea floor reflectors and a lower transparent layer. Beneath the surface unit, two distinctive units (CBI2 and CBI3 on Figure 21) readily identify the basin floor type stratigraphy. These two seismic units present a distinctive sequence of an horizon with moderate acoustic transparency sandwiched between two high amplitude horizons with hummocky, discontinuous reflectors showing abundant diffraction hyperbolae. This sandwiched sequence can be identified by the shift from high to low amplitude and back again which is recognized on the seismic lines as a shift from a discontinuous hummocky dark band to a chaotic light band and then the lower dark discontinuous diffracted layer. The deepest basin floor seismic unit (CBI4 in Figure 21) is made up of an average of 0.3 sec of continuously layered reflectors overlying oceanic basement. These basal sedimentary reflectors strongly resemble those typically associated with turbidites.

The fourth major seismic stratigraphic province recognized in the Colombia Basin by Lu and McMillen is characterized by fan type stratigraphy. Two variations of fan stratigraphy were recognized, one from the more

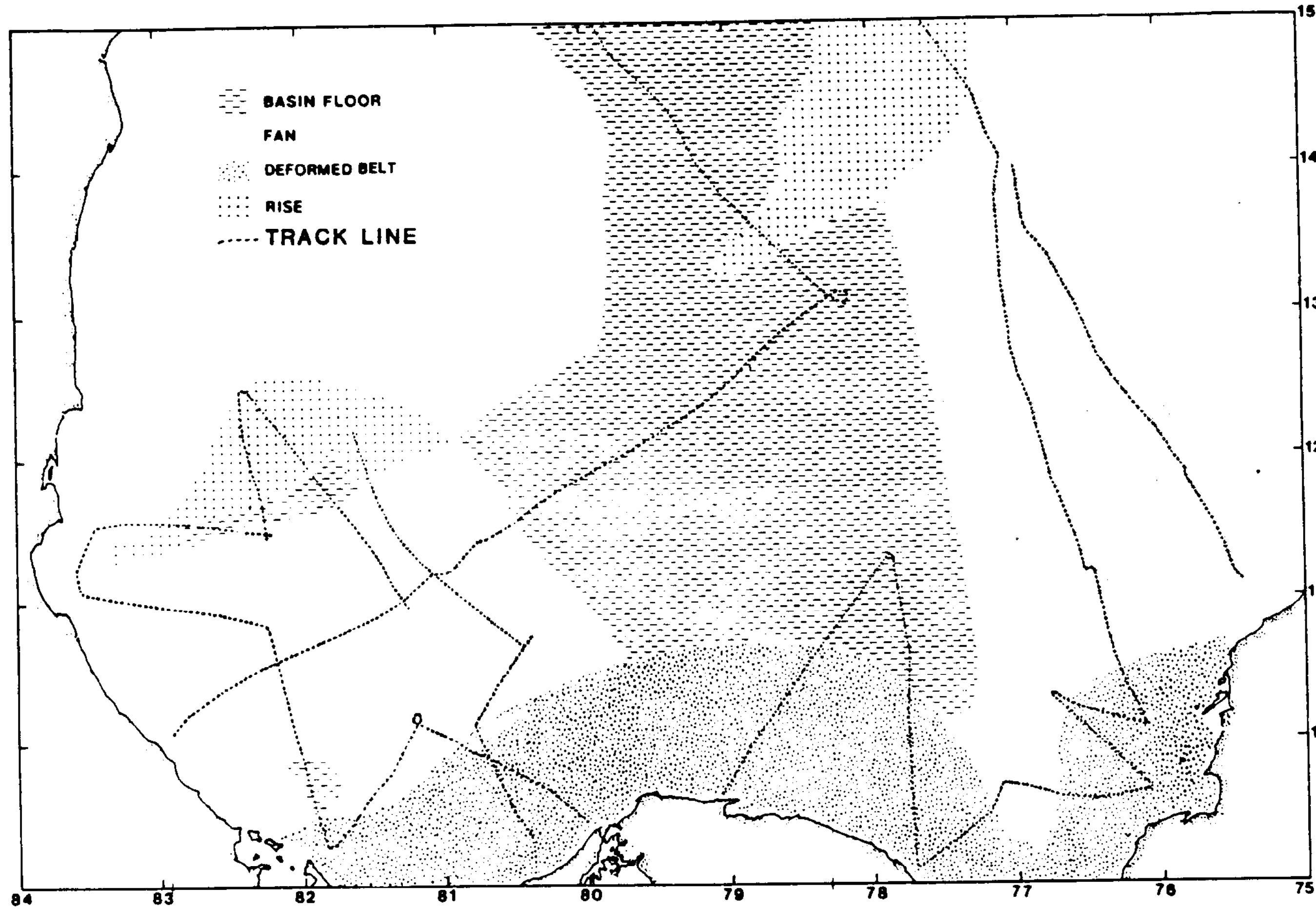
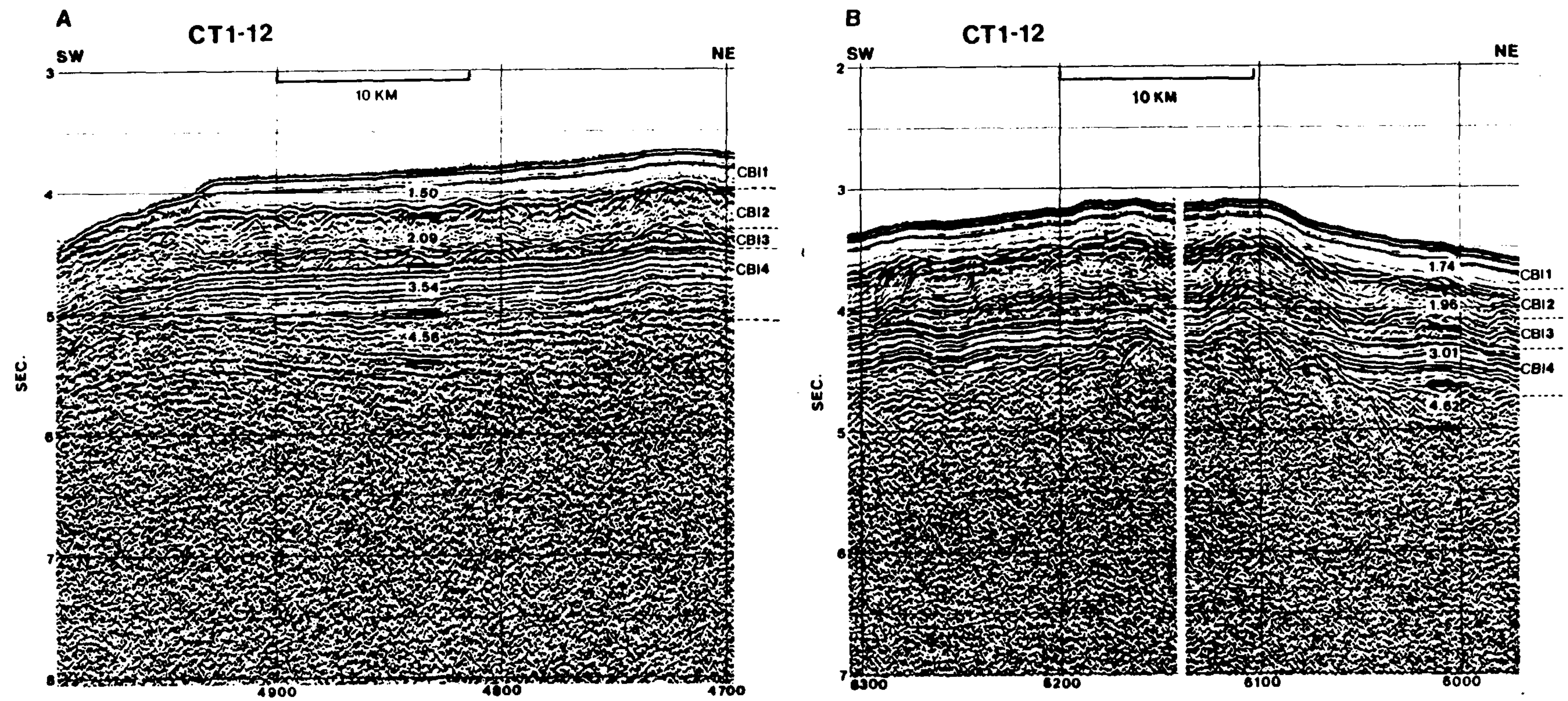


Figure 20. SEISMIC FACIES OF THE WESTERN COLOMBIA BASIN

After Lu and McMillen, 1983



NUMBERS BETWEEN HORIZONTAL BARS ARE CALCULATED SEISMIC VELOCITIES IN km/sec

Figure 21. SEISMIC SECTIONS ILLUSTRATING BASIN FLOOR TYPE STRATIGRAPHY

After Lu and McMillen, 1983

western Panama-Costa Rica Fan and one corresponding to the Magdalena Fan (Figures 2 and 20). The two variants differ principally in that the seismic velocity of the basal sedimentary unit of the Panama-Costa Rica Fan is much higher (4.56 vs 2.92) and the reflectors of the Panama-Costa Rica Fan are fewer and more robust than those from the Magdalena Fan (Figure 22). Lu and McMillen stated that the fan type stratigraphy is quite complex, and its division into four seismic units is somewhat arbitrary.

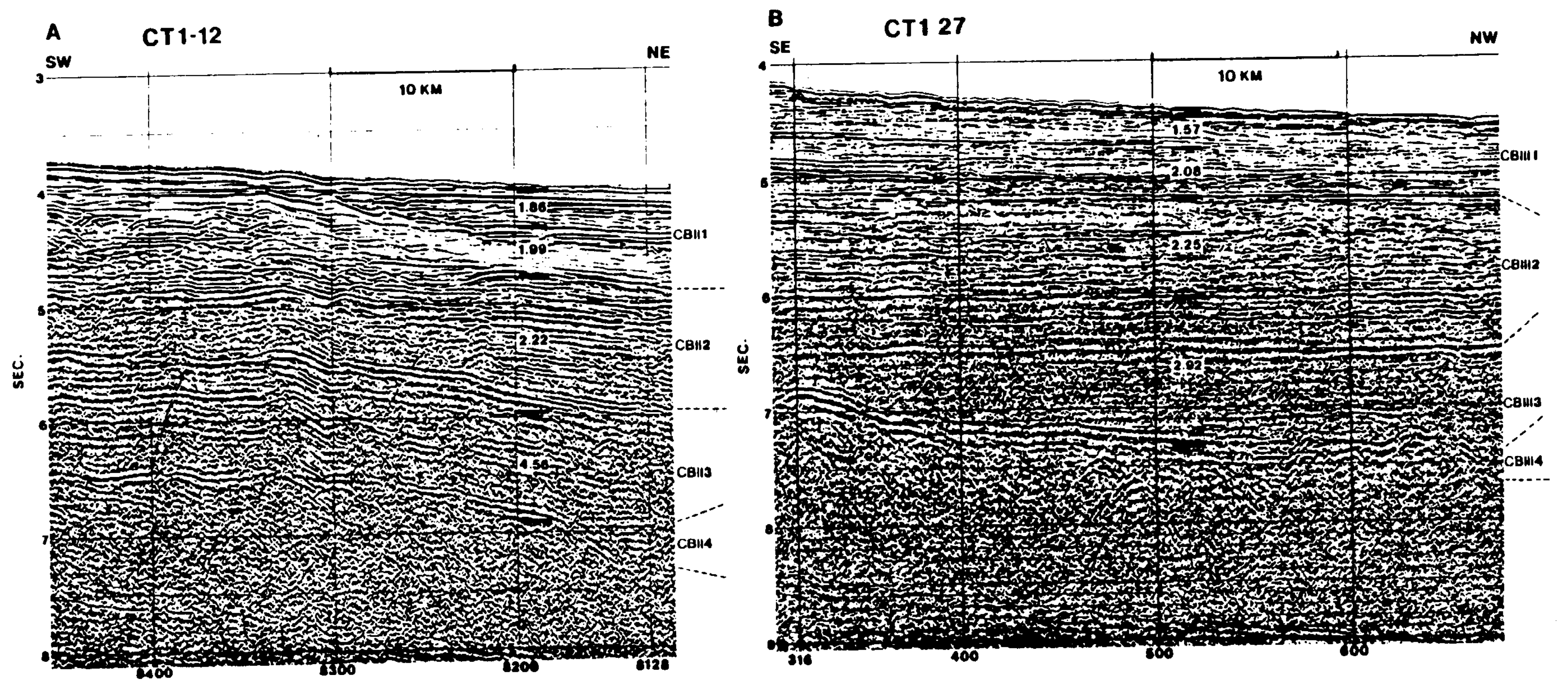
The seismic facies map of Lu and McMillen (1983; Figure 20) is based on a limited number of high quality multichannel seismic lines. Transitions from one stratigraphic style to another are accurately plotted only near the seismic lines; lack of control makes the boundaries approximate elsewhere. As turbidites are principal lithology inferred to be represented by fan type seismic stratigraphy, it is worthwhile to compare the inferred turbidite distribution with a similar map compiled by Prell (1978). Prell's map (Figure 14) was prepared from shallow cores of Pleistocene sediments and from single channel seismic lines with less resolution, but superior areal coverage in the abyssal plains of the Colombia Basin.

A seismic stratigraphic study of the Magdalena Fan using single and multichannel data was published by Kolla et al. (1984). Using the improved penetration of multichannel seismic data, the sediment thickness above basement was determined to range from 5,000 to 7,000 m on the slope to 2,000 to 3,000 m at the distal fringe of the fan.

The authors divided the Magdalena Fan stratigraphy into six seismic units (Figure 23). The basal sequence, unit A, was located only in isolated basement depressions and consists of highly reflective layers. Unit B tends to be transparent with parallel but relatively discontinuous reflectors. Unit C is characterized by more distinct parallel reflectors which resemble those identified in deeper water as due to turbidites. Units A through C thin shoreward and seaward.

Units D through F thicken landward (Figure 23). The reflectors show distinct channels and levees, with progressively larger channel features landward. These upper three units were interpreted to constitute major terrigenous influx to the basin due to principal phases of the Andean orogeny. Thus, these synorogenic units should be datable by correlation of documented tectonic pulses with seismic sequences showing evidence of rapid accumulation. The authors speculated that the contact between units D and C may correspond with Hopkins' (1973) reflector 5 of the Aruba Gap (Figure 19) which was dated as middle Miocene by tying to DSDP Site 153. Kolla et al. (1984) base this supposition on the coincidence higher sedimentation rate of strata above both Hopkins' reflector 5 and their own unit C-D contact. If that assumption is roughly true, then unit D was deposited in early to middle Miocene. Unit E was then dated as late Miocene to Pliocene. The uppermost seismic unit identified in the Magdalena Fan, unit F, is thought to represent sediments derived from the most recent and intense Andean orogeny which began in middle Pliocene. Thus sequence F is of middle Pliocene to Holocene age.

Besides the vertical sequence of reflectors, Kolla et al. (1984) investigated the change of fan morphology from shallow to deep water. The Magdalena Fan was found to display the typical fan morphological characteristics as outlined by Normark (1978). The division of the Magdalena Fan into an upper fan, middle fan, and lower fan sections with seaward



NUMBERS BETWEEN HORIZONTAL BARS REPRESENT CALCULATED SEISMIC VELOCITY IN km/sec

Figure 22. SEISMIC SECTIONS ILLUSTRATING FAN TYPE STRATIGRAPHY

After Lu and McMillen, 1983

FIGURE 23, Seismic Line 127, Magdalena Fan, is located in the pocket at the end of the report.

diminution of channels and associated levees is illustrated in Figure 23. The morphologic, seismic, and assumed sedimentological characteristics of each fan section are summarized in Table 3.

Multichannel seismic lines across the South Caribbean Deformed Belt north of Colombia and Venezuela acquired by LDGO were presented in an article by Ladd et al. (1984). Three of the lines--129, 130, and 132--were taken in the eastern portion of the Colombia Basin study region. Lines 129 and 130 (Figures B2 and B3) cover the same area northeast of the Magdalena Fan that was studied by Krause (1971) using single channel data.

Line 129 (Figure 24) crosses the margin just off of the Santa Marta Massif and intersects the Aguja Canyon (Figure 17). The canyon was cut into a well stratified sediment apron 1 to 2 sec thick (1,000 to 2,000) m). Beneath this prograded sequence, chaotic reflections suggest an accretionary complex of folded and faulted basinal sediments similar to that noted by Lu and McMillen (1983) in the deformed belts 350 km to the southwest. Some folding does occur in the upper sequence. The diminution of fold amplitude upward in the section suggests that gentle folding may have taken place concurrently with deposition.

Section 130 (Figure 25) crosses the margin 100 km northeast of line 129 (Figure 17). Line 130 cuts through a large forearc basin, the Rancheria Basin. The sediments overlying the slope landward of the Rancheria Basin are similar to the stratified section of line 129. Numerous unconformities can be traced in the sediments of the Rancheria Basin landward through the slope sediments. The intensely deformed sediments of the accretionary prism on line 130 are covered by only a thin (0.10 sec) stratified sequence. Even this surface layer appears to have been recently faulted at shot point 3,785. Landward dipping imbricate thrust faults are well illustrated in line 130. The turbidites and hemipelagites which cover the entire slope of line 129 appear to have been trapped and accumulated in the forearc basin of line 130. The bathymetric map compiled by Krause shows that turbidity currents of the Rancheria Basin are drained onto the abyssal plain by a deep canyon adjacent to line 130. Thus, the accretionary wedge of line 130 has received only hemipelagic sediments from the nepheloid layer of the turbidity flows in the Rancheria Basin. The shallower and more pronounced deformation of the accretionary prism illustrated by line 130 may not necessarily represent more intense or recent deformation than experienced near line 129; the slow sedimentation of the accretionary prism at line 130 has not covered the deformed blocks as deeply or as rapidly as on line 129 resulting in more exposed and better defined compressional features.

Section 132 near the eastern limit of the study region (Figure 17) was recorded over the deformed margin south of the Aruba Gap (Figure 26). The section provides data on the continental rise adjacent to the abyssal plain sections of Hopkins (1973) discussed previously. The sedimentation of the margin near line 132 represents a style intermediate between that assumed for lines 129 and 130. A forearc basin exists on line 132, but it is less well developed than the Rancheria Basin on line 130. A few minor unconformities and mild compressional deformation are noted landward of shot point 800. A continuous sedimentary apron covering the accretionary wedge is thinner than that on line 129 but much thicker than the sediment cover draped over the deformed terrane on line 130. Apparently the poorly defined forearc basin on line 132 collected some terrigenous sediment which was thus prevented from

TABLE 3.

SUMMARY OF SEISMIC AND MORPHOLOGIC CHARACTERISTICS OF MAGDALENA FAN
After Kolla et al., 1984.

Characteristics	Upper Fan	Middle Fan	Lower Fan
Gradient	1:60 to 1:110	1:110 to 1:200	<1:250
Longitudinal profile and relief	Irregular; usually >25 m	Irregular to smooth; 6-20 m	Smooth; <5 m
Channels and levees	Channel depth up to >100 m; levee heights up to >100 m; limited number of channel (valley)-levee complexes	Channel depth 30-40 m or less; levee height 20 m or less; numerous channels	Channel depth <20 m; levee absent; few channels
3.5 kHz	Distinct echoes with continuous subbottom reflectors; regular hyperbolae; sediment waves common	Distinct to indistinct echoes, with continuous to fuzzy subbottom reflections; regular hyperbolae; sediment waves common	Indistinct echoes with few or no subbottom reflectors; poor to no penetration; smooth, flat sea floor
Multichannel Seismics	Overlapping or coalescing wedge-shaped levee sequences; channel floors may contain high-amplitude, discontinuous reflections, and onlap-fill sequences	Discontinuous, hyperbolic, and chaotic reflections common; coalescence of small wedge-shaped reflections in upper middle fan; mounding due to many small channel-levee complexes	Relatively continuous, flat reflections
Lithology	Coarse-grained sediments in channels; dominance of fine-grained sediments in other areas	Type of sediment intermediate between upper and lower fan	Coarse-grained (sand) sediments dominate
Processes	Channelized and overbank-spilled turbidity currents; slumping: from continental slope, within channels, and on back sides of levees	Channelized and overbank-spilled turbidity currents; unchannelized turbidity currents; slumping and debris flows	Unchannelized turbidity currents; debris flows

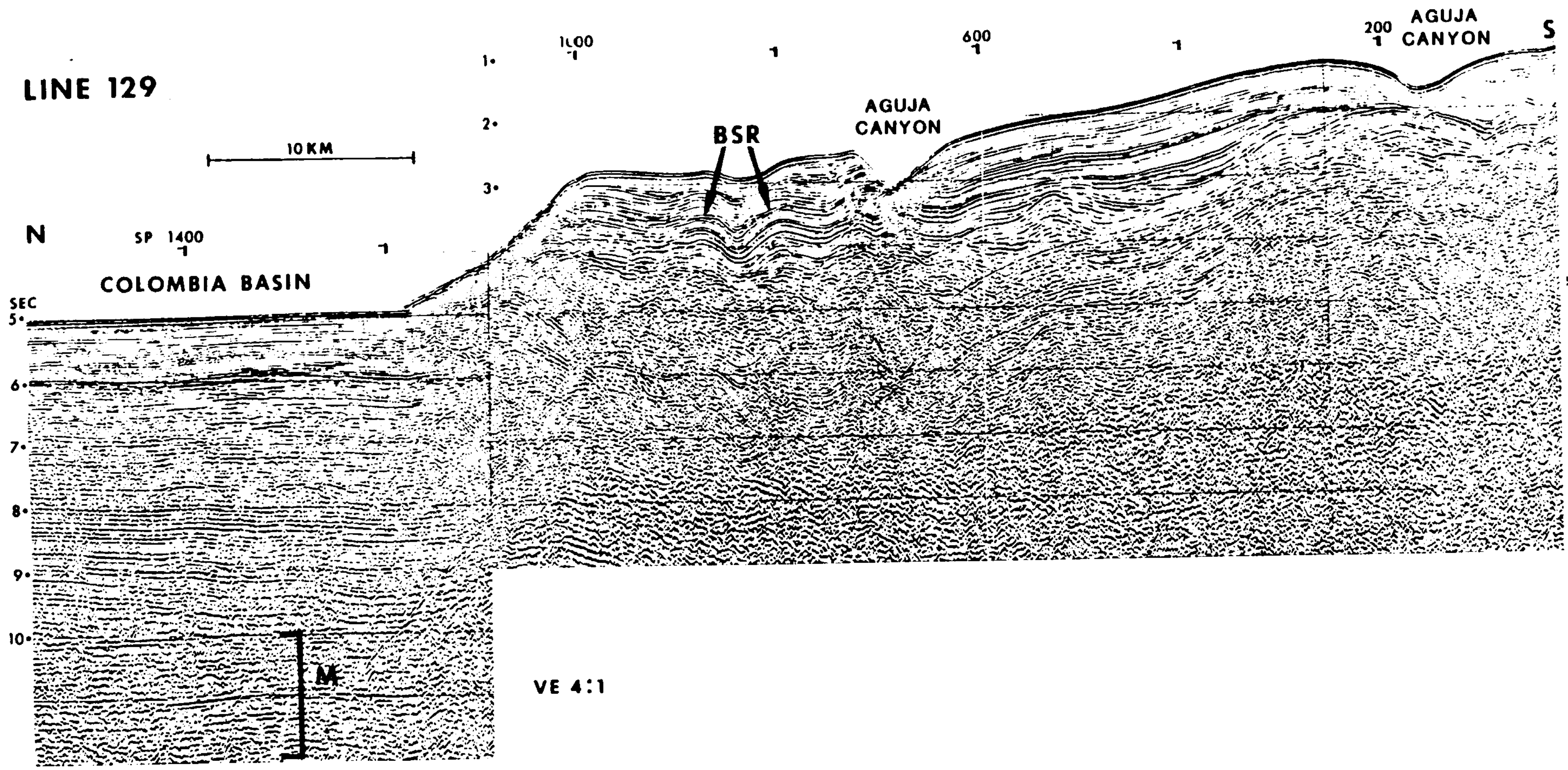


Figure 24. SEISMIC LINE 129 ACROSS COLOMBIA CONTINENTAL MARGIN, OFFSHORE OF SIERRA DE SANTA MARTA

After Ladd et al., 1984

FIGURE 25, Seismic Line 130 Across Colombia Continental Margin, Offshore of Sierra de Santa Marta, is located in the pocket at the end of the report.

FIGURE 26, Seismic Line 132 Across Colombia Continental Margin, Offshore of Guajira Peninsula, is located in the pocket at the end of the report.

reaching the accretionary complex. Landward-dipping reflectors are seen beneath the accretionary wedge from 7 to 9 seconds of depth between shot points 2200 and 1600. This indicates that the wedge of deformed sediments is indeed overthrusting rocks of the Aruba Gap abyssal plain.

A few short segments from LDGO multichannel lines from the Aruba Gap were presented in a paper by Stoffa et al. (1981) concerning the possibility of sedimentary layers beneath the B" horizon. The lines were located near those used by Hopkins (1973) to infer a mixed sedimentary-volcanic sequence above the basement of the Aruba Gap. Stoffa et al. (1981) confirmed the presence of sub-B" reflectors, but concluded that the rocks were probably flow basalts. The quality of the published lines did not permit any refinement of Hopkins' (1973) stratigraphic analysis of Tertiary and Cenozoic sediments of the Aruba Gap.

Structural Setting

The structural makeup of the Colombia Basin study region is complex. Application of plate tectonics does not fully resolve this structural complexity. Much recent progress has been made in understanding the plate motions of the Caribbean and eastern Pacific regions, but traditional views of rigid plates interacting only at boundaries must be modified to adequately explain the features of the Colombia Basin study region.

The deep central part of the Colombia is composed of faulted basement blocks overlain by an average of 2,000 m of sediments. The sediments are draped and ponded without deformation and are also faulted and folded, reflecting syn- and post-depositional deformation. The north and east margins of the Colombia Basin, the Nicaragua Rise and Beata Ridge, are complexly faulted basement blocks draped with thin pelagic sediments. These terranes are typically uplifted 2,500 m above the adjacent basin. The timing and style of deformation of these bounding highs are unclear, but the Hess Escarpment which separates the Nicaragua Rise appears to have experienced left lateral movement in the Tertiary. The southern margin of the Colombia Basin is bounded by deformed belts characterized by compressional folds, thrust faults, and mud diapirism. The orientation of the deformed belts suggests that some of the formative displacement must have been strike-slip, but compressional features are evident throughout both belts.

Basement

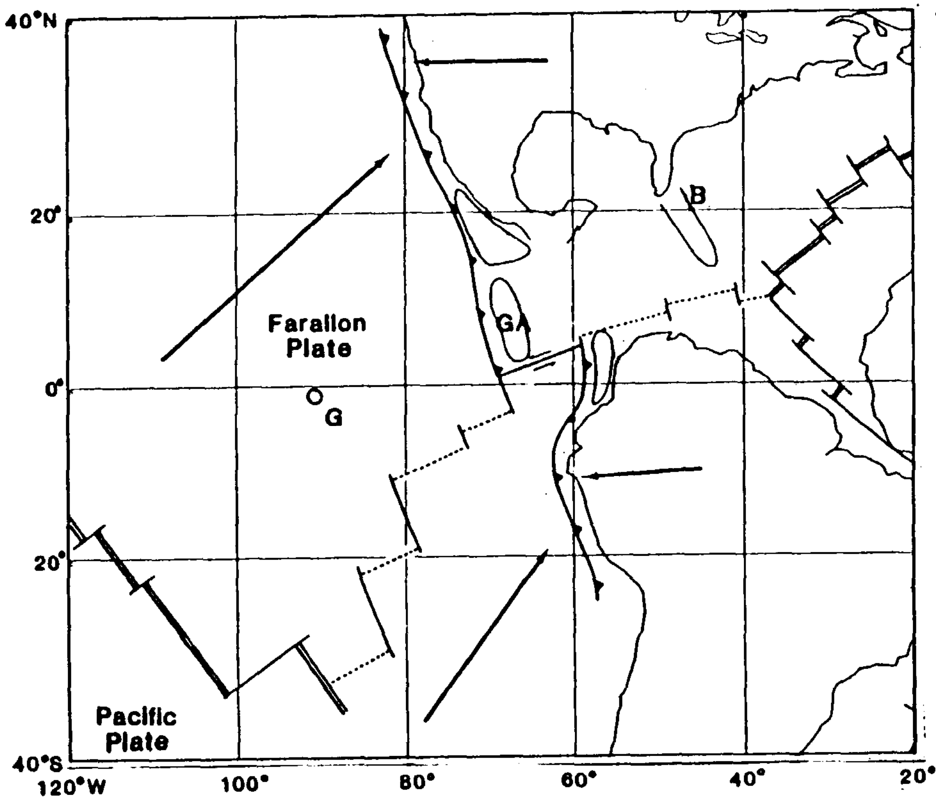
The basement rock underneath the study region is inferred to be oceanic crust with some anomalous features. The thickness of the crust under the Colombia Basin was determined by seismic refraction to be about 12 km, twice as thick as typical for ocean basins (Fox and Heezen, 1975; Edgar et al., 1971). Although early studies detected a unique Caribbean two-component crust, Ludwig et al. (1975) concluded that the basin in the Colombia Basin had a normal range of seismic velocity and was unusual only in being so thick. They proposed that voluminous basalt flows over the basement which were responsible for the widely reported sub-B" reflectors depressed the basement resulting in the anomalously thick crust which was otherwise typical oceanic crust.

Although some magnetic anomalies exist in the region, they are too weak and irregular to determine the age of the crust or the location of the spreading center from which it formed. Basalt flows and diabase sills correlative with reflector B" drilled by DSDP Leg 15 were dated as old as Turonian (Edgar et al., 1973). The existence of a thick sequence of volcanic and/or sedimentary layers beneath B" indicates that the crust may be much older. Igneous rocks from adjacent Caribbean land areas thought to be correlative with sub-B" rocks have been dated as Jurassic to Late Cretaceous (Duncan and Hargraves, 1984).

No consensus exists among researchers on the place of origin of the Colombia Basin crust. Early views envisioned a simple small basin formed in its present location by conventional sea floor spreading resulting from the separation of North and South America. The similarity between the very thick Caribbean crust and Pacific oceanic plateaus was noted by Burke et al. (1978). Sykes et al. (1982) observed that the thick oceanic crust of the Caribbean Plate was not subducted at its convergent boundary with the Atlantic plate along the Lesser Antilles arc, which is also analogous to the Java oceanic plateau. Burke et al. (1978), Pindell and Dewey (1982), Sykes et al. (1982) and others have proposed plate tectonic scenarios whereby the oceanic crust of the Caribbean Plate was formed by sea floor spreading in the region of the Pacific Ocean.

These investigators used various means to arrive at the concept of allochthonous Caribbean crust, such as magnetic anomalies, rates of sea floor spreading, and paleogeographic reconstructions. All of these studies were concerned with relative plate motions. Duncan and Hargraves (1984) were able to determine the absolute movements of plates in the Caribbean region in the mantle reference frame. They also determined that the sub-B" lavas were probably erupted from the Galapagos Hot Spot. The following summary of plate movements as illustrated in Figure 27 is based on work by Duncan and Hargraves (1984).

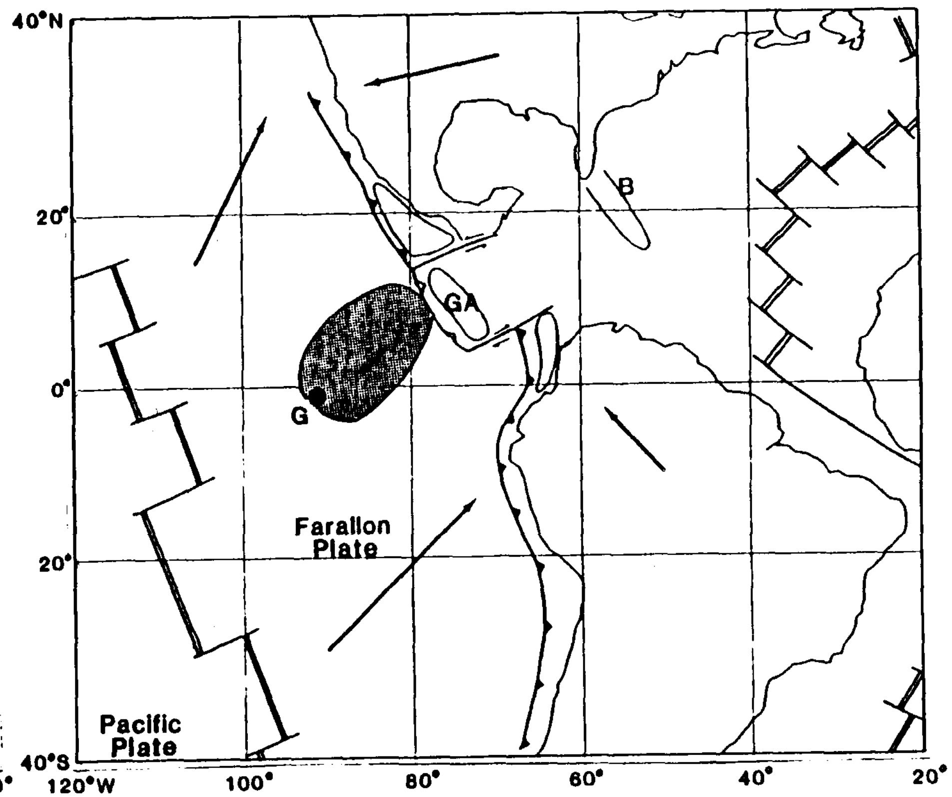
Concurrently with spreading or shortly thereafter, the proto-Caribbean crust was flooded by tremendous volumes of basalt which constitute the sub-B" rocks. According to these hypotheses, thin, typical oceanic crust was existent between North America and South America in the area presently occupied by the Caribbean Plate. Between 100 and 70 m.y. the thick crust that was to become the Caribbean Plate moved eastward, until it reached a subduction zone west of an island arc which was to become the Greater Antilles (Cuba, Hispanola, Jamaica, Puerto Rico). Since the proto-Caribbean Plate was too buoyant to be subducted, the Greater Antilles island arc was sutured to the plate and began to move eastward with it, subducting oceanic crust along its east border as it went. Crust was also being subducted at the western border of the proto-Caribbean Plate forming a narrow island arc which was to become Panama. The eastward moving Greater Antilles island arc collided with the Bahama Platform, a part of the North American Plate at around 38 m.y.B.P. Cuba became welded to the North American Plate, while Hispanola, Jamaica, and Puerto Rico continued eastward as part of the Caribbean Plate. Continued eastward movement of the Caribbean Plate and westward movement of the South American Plate resulted in the collision of the Panama island arc with northwestern South America and subsequent uplift of the Panama Isthmus around 3 m.y. ago.



G IS GALAPAGOS HOTSPOT. B IS BAHAMA PLATFORM. GA IS GREATER ANTILLES ARC

Figure 27A. PLATE POSITIONS AT 100 m.y. B.P.

After Duncan and Hargraves, 1984



LARGE VOLUMES OF BASALTS ERUPTED AT THE GALAPAGOS HOTSPOT FORMED AN OCEANIC PLATEAU (STIPPLED PATTERN) BETWEEN ABOUT 100 AND 75 m.y., WHICH COLLIDED WITH THE GREATER ANTILLES ARC IN THE LATE CRETACEOUS

Figure 27B. PLATE POSITIONS AT 80 m.y. B.P.

After Duncan and Hargraves, 1984

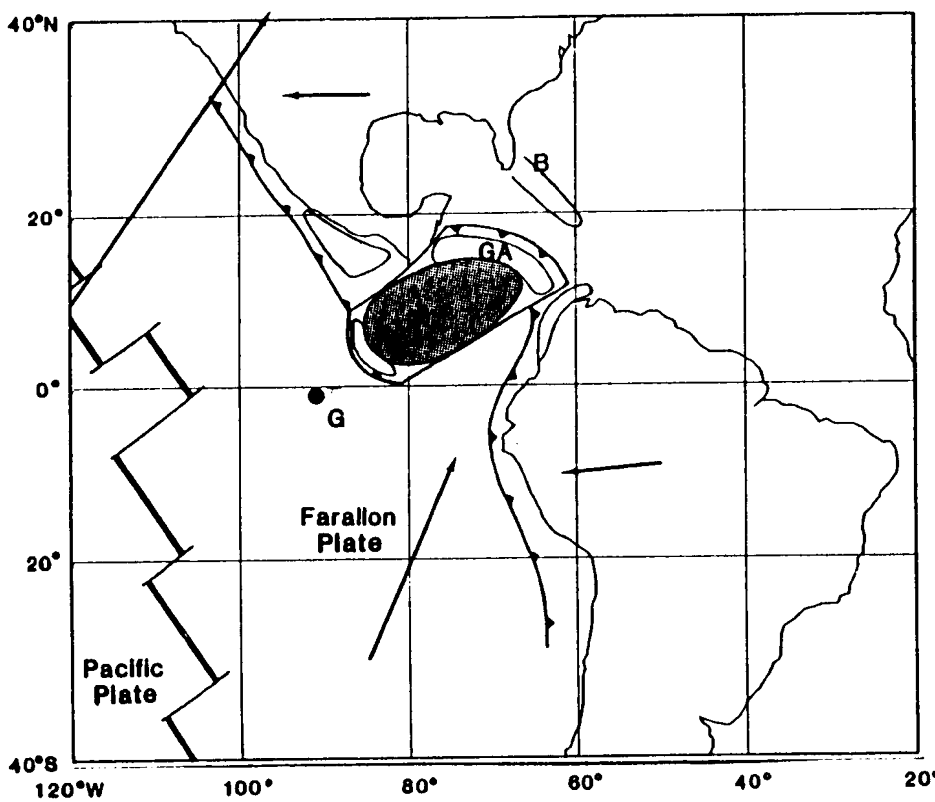


Figure 27C. PLATE POSITIONS AT 60 m.y. B.P.

After Duncan and Hargraves, 1984

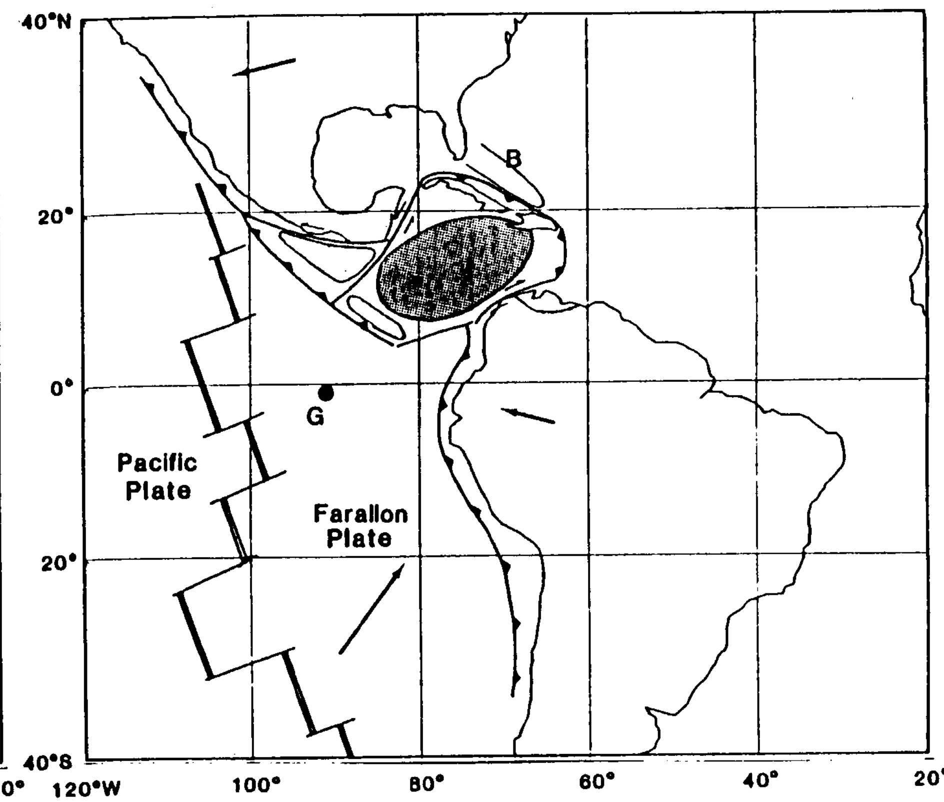


Figure 27D. PLATE POSITIONS AT 38 m.y. B.P.

After Duncan and Hargraves, 1984

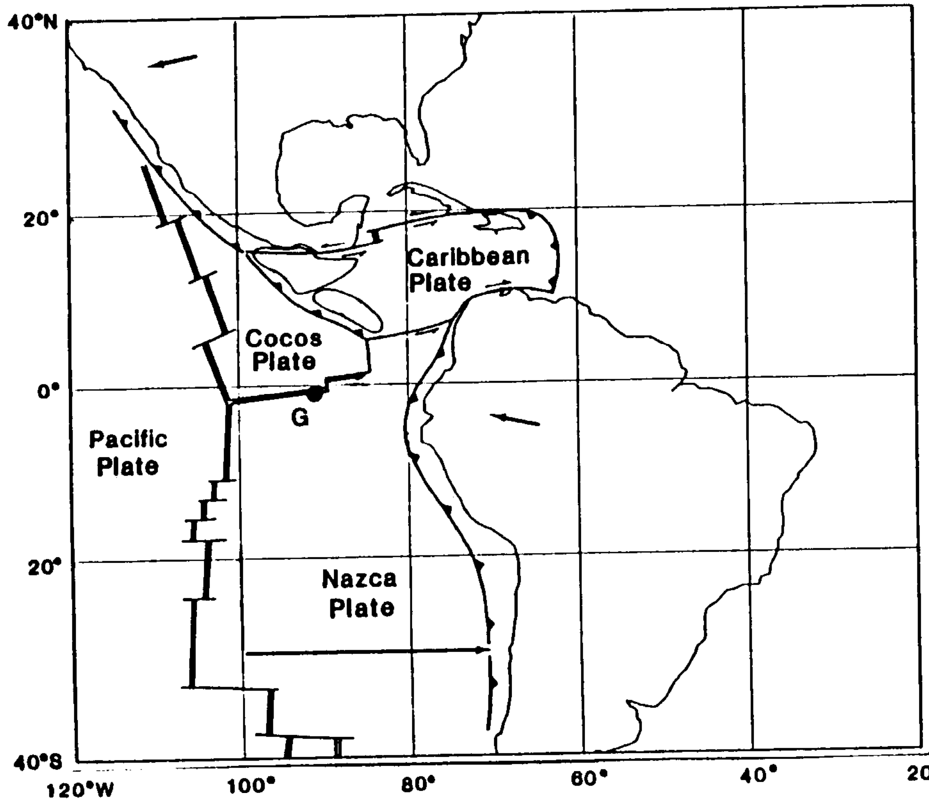


Figure 27E. PLATE POSITIONS AT 21 m.y. B.P.

After Duncan and Hargraves, 1984

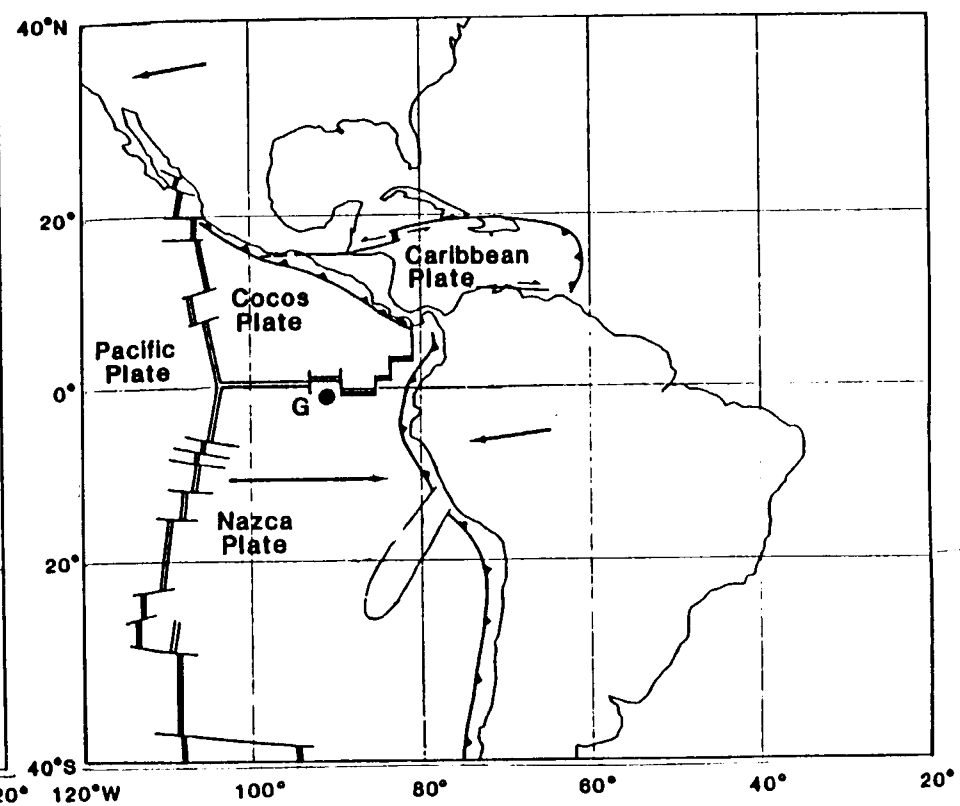


Figure 27F. PLATE POSITIONS AT PRESENT

After Duncan and Hargraves, 1984

Colombia Basin

Structural features of the Colombia Basin have been maped by Case and Holcombe (1980) from single channel seismic data. They mapped recognizable faults, both those which penetrated overlying sediments and basement faults which produced monoclinal flexure of the sedimentary section, and basement highs (Figure 28). Several directional trends of structures are apparent in Figure 28. However, the exact trend of most mapped features are not precisely determined. The trends of features which were only intersected on one seismic profile were assigned as normal to the track of the section; thus, only the structures intersected by two or more seismic profiles have accurately plotted trends (Case and Holcombe, 1980). Regions in which tracks are preferentially aligned may show a perpendicular alignment of structures. Regardless of these limitations cited by the authors, the strike of faults and basement uplifts is generally northeast in the eastern part of the Colombia Basin (72° W - 78° W) and northwest in the western portion (78° W - 81° W). The fault density of the abyssal plain and fan provinces is greatest near the Nicaragua Rise and Beata Ridge, and least in the fan and central basin, distant from these uplifts. This effect may be amplified by the poor acoustic penetration by single channel seismic lines of the thick turbidite sequences of these areas.

Multichannel seismic methods have elucidated structural deformation beneath thick sedimentary sequence. When coupled with core and seismic stratigraphic interpretations, a better idea of the timing of faulting can be obtained also. Biju-Duval et al. (1978) published a short segment of a NE-SW multichannel seismic line from the abyssal plain 80 km west of the southern termination of the Beata Ridge. Their published interpretation of the line indicated large faulted basement blocks with vertical separations of up to 1 sec (approximately 1,500 m). The faulting showed evidence of deformed sediments which appear to be correlative with the CBI4 seismic stratigraphic unit of Lu and McMillen (Figure 21) probably of Tertiary age. One particularly large uplifted block seen on the seismic line of Biju-Duval et al. (1978) appears to have produced a drape fold in distal turbidite deposits which may be equivalent to the Miocene D unit of Kolla et al. (1984).

The area of the study region in which DSDP Sites 154 and 502 were located is structurally disturbed. Figure 11 illustrates the structural setting of these sites which was revealed by single channel seismic profiling to consist of a large horst 60 km wide and 300 m high upon which Site 502 was drilled and a much smaller faulted ridge 80 km to the southeast where Site 154 was spudded. Closely spaced seismic control in this area allowed Case and Holcombe (1980) to more fully delineate these structures, the larger of which has come to be called Mono Rise (Holcombe, 1977; Figure 28). Lu and McMillen (1983) include a section of a multichannel seismic line (CT1-12) which crosses Mono Rise and the subordinate western ridge 80 km north of and parallel to the seismic line acquired on DSDP Leg 15. This section (Figure 29) better illustrates the structural style of this deformation. Mono Rise appears here to be a gentle upwarping of the basement, rather than the sharply block faulted structure profiled to the south by DSDP Leg 15 (Figure 11). The small ridge upon which Site 154 was located is shown in the multichannel line to be the result of east dipping imbricate thrust or reverse faults most likely due to horizontal compression. This section also illustrates

FIGURE 28, Fault Distribution in the Colombia Basin Study Region, is located in the pocket at the end of the report.

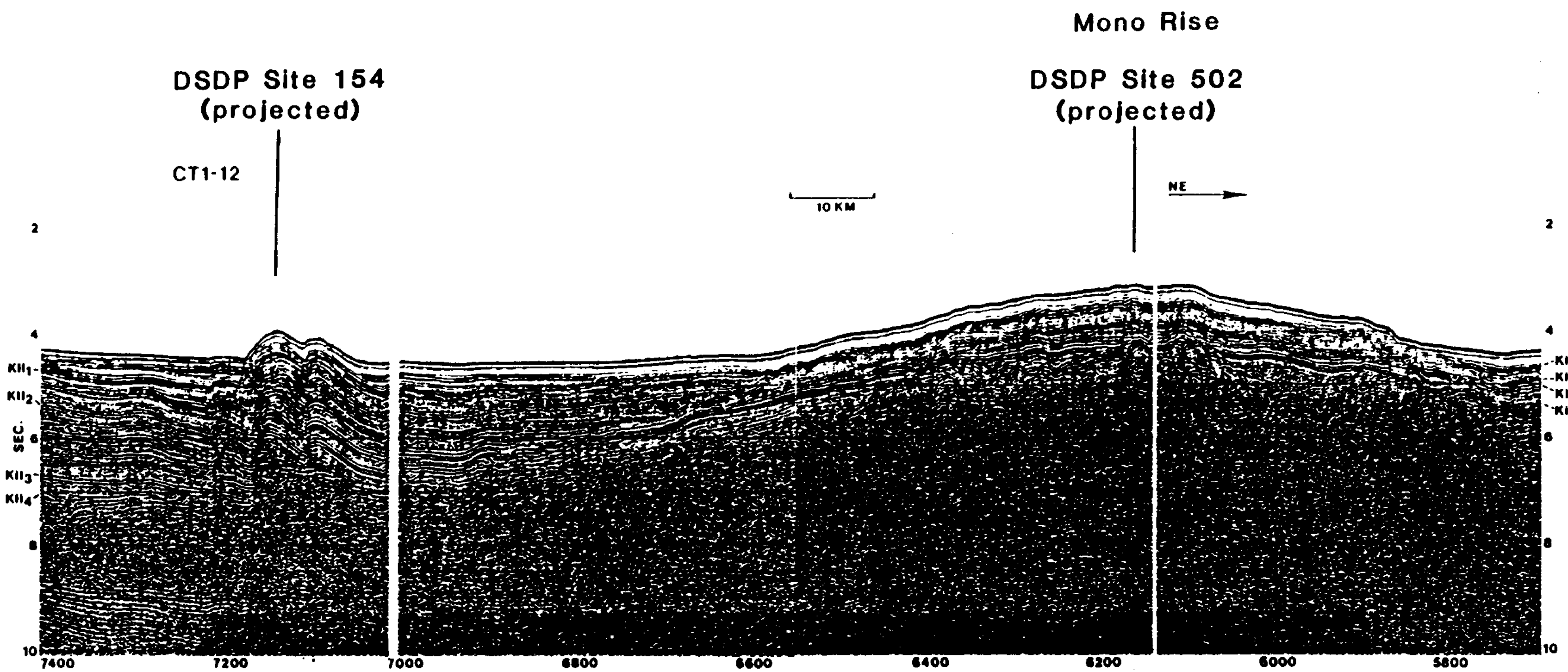


Figure 29. SEISMIC LINE CT1–12, SOUTHWESTERN COLOMBIA BASIN

After Lu and McMillen, 1983

a lateral change from Lu and McMillen's (1983) fan type stratigraphy on the west (left) to basin floor type stratigraphy at or near shot point 6,800.

The section also confirms the speculation by the DSDP Leg 68 scientists (Prell et al., 1983) that Mono Rise was uplifted before the smaller ridge upon which Hole 154 was drilled. Only the lowermost seismic unit (CBI-4 of Lu and McMillen, 1983) is generally continuous over the entire section. Uplift of Mono Rise during or prior to the deposition of the next seismic unit (CBI-3) is shown by a thick coeval sequence of turbidites west of Mono Rise. This indicates that Mono Rise formed a topographic barrier to turbidity currents from the Panama-Costa Rica area and thus received direct pelagic sedimentation. The smaller ridge has sedimentary layers identical to the adjoining basin showing continuous turbidite deposition across the plain without topographic interference. A distinct change in seismic character of the sediments east of the small ridge to more transparent basin style-like stratigraphy begins at 5.0 sec at shot point 6,600 and progresses westward in more recent sediments. This suggests that uplift of the small ridge began and continued during the deposition of CBI-2. The more transparent reflectors are interpreted here as being more pelagic in character; uplift of the ridge progressively blocked increasing amounts of turbidites impinging from the west. The uplift appears to have been essentially complete by the time deposition of CBI-1 (sediments above K1, on Figure 21), giving a transparent apron of pelagic sediments 0.3 to 0.4 sec thick over the ridges.

Seismic line CT1-12 can be used to estimate whether organic-rich sediments are within the gas hydrate stability zone. Turbidite sediments with as much as 6.9% organic carbon were cored at DSDP Site 154, 80 km south of line CT1-12 on an extension of the small ridge illustrated in Figure 29. The organic-rich, gassy sediments were found about 150 m subbottom beneath barren pelagic carbonate ooze. The distinct reflector at 0.2 sec subbottom on single channel seismic sections (Figure 11) was correlated with the top of this organic-rich turbidite sequence. The resolution of line CT1-12 is such that reflectors on the ridge can be traced into the adjacent basin. This small ridge is a composite of three thrust fault blocks ramped upon each other giving three ridges, two of which have prominent sea floor relief. The shallowest turbidite reflector on the small eastern ridge is at 0.2 sec subbottom. If this reflector is assumed to be equivalent to the organic-rich beds of Site 154, gas hydrate prone sediments would be present at 0.5 sec subbottom depth in the trough between the ridge and Mono Rise. The seismic record on the larger western fault block is not as clear. A strong reflector appears at 0.5 sec subbottom on this block; however, it is not the shallowest prominent reflector as was the previous case. The reflectors above this principal reflector are not continuous and appear to be disrupted by structural deformation or mass wasting on the steep structure. Thus it is possible that sediments correlative with the organic-rich turbidites of DSDP Site 154 may exist above the principal reflector at 0.5 sec subbottom, or that reflector may itself be correlative with the organic-rich turbidites. It is more likely that the Miocene turbidites are represented by the discontinuous reflections at 0.2 sec on the larger ridge. Landward (southwest) of this structure, a strong reflector can be traced as reflector KII_1 to the left edge of the illustrated seismic section. This reflector is as deep as 0.6 sec subbottom near the structure and becomes progressively shallower to the west, being 0.35 sec deep at the edge of the section. If the assumptions of northward continuity of the Pliocene organic-rich turbidites and structural continuity of the ridge on CT1-12 and that drilled as Site 154 hold, then gas prone sediments should exist in the adjacent structural lows at depths of 0.3 to 0.5 sec subbottom. These depths are probably within the gas hydrate stability zones for the area; BSRs on a section from the continental margin south of DSDP Site 154, average 0.5 to 0.6 sec subbottom. Thus even if the turbidites cored at DSDP Site 154 are anomalously rich in organic matter, and were overlain by much leaner turbidites less conducive to gas generation, the sedimentary section in the fan and abyssal plain areas adjacent to the uplifted fault block that was cored should contain sediments with biogenic gas generative capability within the gas hydrate stability zone.

Other seismic sections which were reviewed in preparation for this report showed that the acoustic basement in the Colombia Basin is occasionally faulted with deformation occurring up through part of the Tertiary section, but generally not cutting the upper 0.3 sec of sediments. Some sections do show evidence of very recent faulting, cutting the surface sediments.

Nicaragua Rise

The Nicaragua Rise is a terrane of very thick, complexly faulted oceanic crust which has been uplifted 1,000 to 3,000 m above the level of the Colombia Basin (Case et al., 1984). The transition from the Nicaragua Rise to the Colombia Basin is generally abrupt, and marked by fault escarpments. An exceedingly linear segment of this border between provinces is termed the Hess Escarpment (Figures 1, 2, 3, and 16).

Very little published work is available on the tectonics of the Nicaragua Rise. Seismic profiles reveal fault blocks presumed to be oceanic basement covered by up to 1,500 m of sediments. The rugged topography of the rise has resulted in variable amounts of sedimentary accumulation.

The linearity of the Hess Escarpment suggests that it has resulted from faulting which has a strike-slip component. Case et al. (1984) indicate possible left-lateral displacement on a map without elucidation in the text. Mann and Burke (1984) propose right lateral movement for the most recent movements along the fault based on minor structures where the trace of the escarpment is offset. Holcombe (1977) stated that the continuous sediment cover over the fault, evident on seismic sections, indicates that the escarpment "is not a geologically youthful feature." Burke et al. (1984) claimed post-Eocene movement of 60 km. Case (1975) stated that some faulting on the rise was recent. Our review of available seismic records indicates that evidence of faulting within the sedimentary section of the Nicaragua Rise is rare.

Beata Ridge

Beata Ridge is a large, uplifted, block faulted structure extending from Hispanola to the Aruba Gap and separating the Colombia and Venezuela basins. A series of steep escarpments separates the Beata Ridge and the Colombia Basin. Basaltic rocks, possibly basement, crop out regularly along the west flank of the Beata Ridge (Case and Holcombe, 1980). Faults trend dominantly northwest in the southern section of the ridge and northeast in the northern reaches of the ridge (Case and Holcombe, 1980; Figure 28).

Fox and Heezen (1973) projected the Beata Ridge to have formed in the Late Cretaceous to early Tertiary by block faulting. The Beata Ridge cannot be a simple block faulted uplift because the gravity anomalies indicate that the uplift has been compensated by crustal thickening more so than would be expected in an extensional block faulted regime (Bowin, 1969).

Burke et al. (1984) have proposed that the Beata Ridge was uplifted in response to northerly directed compressional stress generated by the late Miocene to Pliocene collision of the Panama island arc and northwestern South America. This proposed mechanism is claimed by Burke et al. (1984) to be consistent with recent north trending strike-slip faulting in the Beata Ridge.

Marginal Deformed Belts

The North Panama Deformed Belt and the South Caribbean Deformed Belt (Figure 2) are composed of intensely faulted and folded sediments which have either been uplifted from the Colombia Basin or deposited directly on the margin. Seismic profiles of the Caribbean continental slope and rise indicate deformation similar to that observed along convergent plate boundaries elsewhere in the world. The geometry of the deformed belts, however, dictates that the displacement causing the observed structures must have some strike-slip component.

The continental shelf offshore of the north coasts of Panama and Colombia varies in width from 8 km to 80 km. The few quality seismic sections which are available show that the continental shelf is composed of folded and faulted sediments covered by an apron of ponded sediments which fills structural relief producing a planar, gently inclined surface.

The continental slope and rise north of Panama and Colombia vary in width and gross morphology. The width of the deformed belt varies from 60 to 100 km north of Panama with a mean slope of 3°. Southwest of the Magdalena Delta, the northeast trending deformed belt is narrow, 40 - 50 km, and steeper, 4°. Offshore of northeastern Colombia, the deformed belt again becomes wider, 100 - 130 km and less steep, 3°. Some profiles, notably 130 (Figure 25), display well developed convergent margin structure, consisting of an accretionary prism of imbricately thrusted and folded blocks, followed shoreward by a well defined forearc basin. Other profiles, eg. PN-1 (Figure 3), have no distinct slope break and forearc basin developed, showing only an accretionary wedge with a continuous gradient from the abyssal plain to the continental shelf.

Most seismic sections of the margin show distinct thrust faults and drag anticlines. However, all postulated past and present reconstructions of plate movements in the area require some component of strike-slip motion in addition to convergent motion to produce the observed spatial configuration of the Caribbean and eastern Pacific areas. Merely the arcuate shapes of the Panamanian coast line and Colombian coast line dictate that linear convergence between the Caribbean and South America and Panama along any bearing would induce substantial shear motion, with some segments of the deformed belts experiencing strike-slip and even divergent motion. Thus a paradox is developed; seismic sections show classic compressive features all along the Caribbean margin, but the geometry of the deformed belt suggests that large segments of the province must be experiencing deformation other than compression.

The early plate movements which produced the Caribbean were previously discussed in connection with the anomalous crust of the Colombia Basin. Briefly, the Caribbean Plate is thought to have moved eastward from the Pacific to its present position between the North American plate to the north, South American plate to the south, the Nazca Plate and the Cocos Plate to the west (Figure 27). The precise locations of the borders of the plates are unclear, especially in the area of the marginal deformed belts. Relative plate motions derived from earthquake focal data are illustrated in Figure 30. The relative motion between South America and the Caribbean has been calculated as west-northwest by Minister and Jordan (1978). However, the magnitude of this convergence is small in comparison with westerly and northeasterly convergence of the Nazca and Cocos Plates upon North and South America.

The most effective solution yet proposed to accommodate the paradox of the observed structures and the necessary causal plate movements is to abandon the simple model of rigid plates with deformation confined to well defined plate boundaries. Some deference to major intraplate deformation, "microplate" interaction, and/or the existence of diffuse plate boundaries with large-scale plate movements accommodated by minor deformation over a broad band of disturbance seems necessary to understand the structure of the deformed belts.

One view expressed by Mattson (1984) is that the southwest corner of the Caribbean Plate comprising the Panama Isthmus and the North Panama Deformed Belt has been compressed between the obliquely converging South American and Cocos plates. Mattson suggested that the convex arcuate shape of Panama may be a result of the southwest corner of the Caribbean plate being caught in this bind. With less space to be occupied between the more massive South American and Pacific plates, that corner of the Caribbean plate then deformed internally and shortened east to west resulting in the curve. Mattson further predicted that continued movement should force the isthmus to double over so as to collapse onto itself and be accreted against the northwest coast of Colombia. Such a mechanism would result in the observed compressional features in their unusual configuration. The simple northwestern convergence of the main body of the Caribbean Plate and the South American Plate would result in the southwestern trending deformation along the Colombia coast. A forced bending of Panama would accommodate the compression by radially directed overthrusting of the Caribbean sea floor, thus producing compressional structures all along the outer limit of the arc of the isthmus.

Another way of solving the deformation problem is to assume that Panama and the Panama Basin of the Pacific Ocean constitute their own plate. However, as proposed by Bowin (1976), plastic deformation of the Panama Plate at its convergent boundary with the Caribbean Plate at the North Panama Deformed Belt is required to be consistent with gravity data. Mattson (1984) reported that J.E. Case considers that Panama is its own distinct plate based on earthquake studies. Lu and McMillen (1983) also mentioned the possibility of plastic deformation or the existence of microplates to account for the observed structure in view of inferred plate motion.

These alternative structural interpretations do resolve the question of an arcuate thrusted North Panama Deformed Belt immediately facing the north-east trending deformed belt off the northwestern coast of Colombia. However

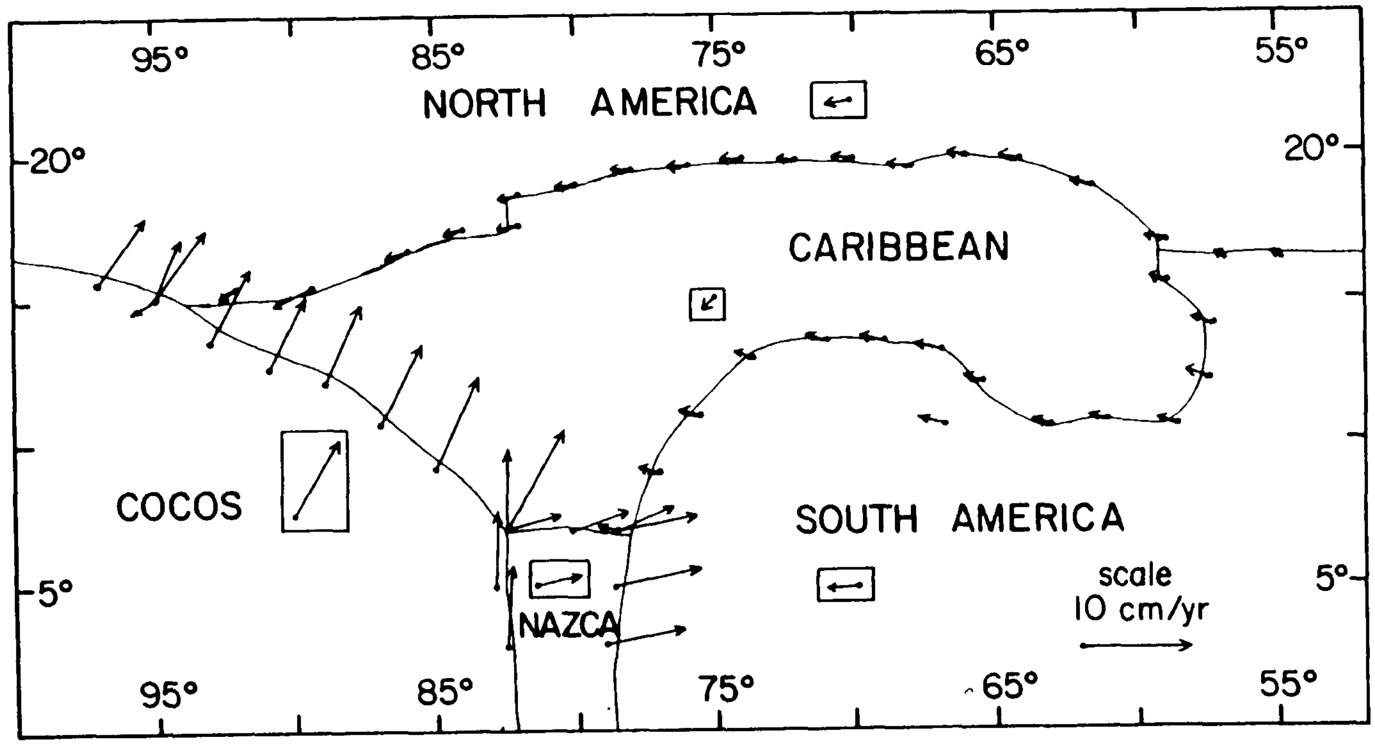


Figure 30. RELATIVE AND ABSOLUTE PLATE MOTIONS OF THE CARIBBEAN REGION FOR THE LAST FIVE MILLION YEARS

After Mattson, 1984

the South Caribbean Deformed Belt north of Colombia and Venezuela is itself arcuate, trending due east and then east-southeast as it is traced eastward from offshore Colombia to Venezuela (Figures 1 and 2). More recent tectonic theories have attempted to reconcile compressive features in the eastern part of the study region with the previously discussed difficulties north of Panama. These more comprehensive treatments require that the marginal belts result not only from interaction of the Caribbean and the South American continent, but also reflect compression resulting from movement of separate large fault bounded blocks of the northern South American Continent. Kellogg and Bonini (1981) showed that the Sierra Perija and Sierra de Santa Marta on the north coast of Colombia are allochthonous thrust sheets which had been displaced to the northwest and was bounded by major northwest and west trending strike-slip faults. Pennington (1981) demonstrated that a shallow dipping (20°) Benioff zone with a northeast strike, presumably representing subducted Caribbean lithosphere, can be documented under northwestern Colombia, including the Sierra de Santa Marta. However, the orientation of this Benioff zone did not match that of a major Benioff zone farther south along the west coasts of Colombia and Equador, indicating that this area of northeastern Colombia was detached laterally from the main portion of the South American continent farther south.

Pennington (1981) noted that large, occasionally active northeast and northwest trending faults in northern Colombia and northwestern Venezuela could accommodate such dislocation. In Pennington's treatment, the deformed belts near the Aruba Gap could be thought of as resulting in the blocking of the Nazca-South American subduction zone by a thick mass of basement rock, the Carnegie Ridge. With subduction prevented, the ridge pushed the northwest part of the South American continent to the north-northeast along left lateral, northeast trending strike-slip faults. Thus the north coast of Colombia would have been pushed north-northeastward toward the Aruba Gap resulting in compressive structures in the deformed belt.

Earlier, Bowin (1976) had proposed a similar mechanism based on gravity anomalies. Bowin (1976) ascribed no definite cause to the fractionation of northwestern South America. His resultant movements resembled Pennington's (1981) except that the east to west compression of the Nazca and South American plates was transferred to not only one northeast shear, but also to a conjugate northwest shear, the boundary strike slip fault of the Sierra Santa Marta (Figure 28). Thus a separated block, termed the Maracaibo block bounded by the lateral faults to the southeast and southwest was displaced north to north-northeast toward the Colombia Basin producing the observed deformed belt orientation landward of the Aruba Gap.

Mann and Burke (1984) presented an integrated interpretation of the recent tectonics of the Colombia Basin. In their model the collision of the Panama island arc and the northwest coast of South America was the cause of the observed deformation. They noted that the North Panama Deformed Belt and the South Caribbean Deformed Belt are approximately symmetrically oriented about the suture zone where they are joined. The North Panama Deformed Belt is smaller than the South Caribbean Deformed Belt, but both are convex to the north. Mann and Burke (1984) proposed that after the collision of Panama and South America about 3 m.y. ago, the continued east to west compression was relieved by forcing lithosphere away from the collision zone by strike-slip movements along conjugate northeast and northwest trending faults. Thus, Panama is being forced northwest with major thrusting relegated to the western portion of the North Panama Deformed Belt (west of 80° W) according to Mann and Burke (1984). These authors retained Bowin's (1976) and Pennington's (1981) concept that east-west compression resulted in decoupling of northwestern South America from the rest of the continent. A block, similar to the Maracaibo block of Bowin (1976) but extending farther eastward was proposed to have resulted in the northerly directed compression near the Aruba Gap. Mann and Burke (1984) also claimed that this northerly push of the fault block into the Caribbean was instrumental in the uplift of Beata Ridge, which occurs in the narrowest part of the Caribbean and thus would have been the first deformed area as it was buttressed between the South American fault block and Hispanola.

Mud Diapirism

The north coast of Colombia is one of the world's principal sites of mud diapirism. Active mud volcanoes and mud diapirs have been documented both onshore and offshore of the Caribbean coast of Colombia (Hedberg, 1980; Shepard, 1973; Duque-Caro, 1984).

Large diapirs beneath and within the sediments of the Magdalena delta and fan were discovered by Shepard et al. (1968) during seismic profiling off of the Caribbean coast of Colombia (Figure 31). More detailed seismic surveys conducted later revealed a large diapir field within the continental slope northwest of the mouth of the Rio Magdalena in water depths of 700 - 1,400 m (Shepard, 1973). The diapirs are aligned in a northeast trending band 20 km wide and over 100 km long, approximately paralleling the anticlines and faults of that segment of the South Caribbean Deformed Belt. The largest of the mud diapirs in the field show up to 200 m of surface relief (Figure 31), but most average 50 m of relief. A full range of piercement and non-piercement structures were found ranging from swells which merely arch overlying sediments, through diapirs similar in form to salt domes of the Gulf of Mexico, to apparent mud volcanoes where the mobile material was erupted onto the sea floor surface. The structure of the diapirs differs from typical salt diapirs in that the beds abutting the diapirs tend to dip downward toward the mud diapir rather than upward. Shepard (1973) concluded that the expansion afforded the overpressured mud upon penetrating to the near surface permitted the beds to collapse downward in response to the volume decrease.

Duque-Caro (1984) has hypothesized that the dominant cause of deformation in the offshore accretionary terrane and in previously accreted onshore provinces of northwestern Colombia is mud diapirism on a massive scale. The Sinu Belt of Duque-Caro (1984) comprises the Colombian portion of the South Caribbean Deformed Belt of Case et al. (1984), the majority of which is the continental margin offshore. Accreted pelagic and hemipelagic deposits are also found in a narrow strip, 5 to 60 km across, onshore from Baranquilla at the mouth of the Rio Magdalena southeast to the north-south suture zone marking the collision of Panama and South America. Further inland from the Sinu Belt, Duque-Caro (1984) mapped an older and less extensive accretionary terrane, the San Jacinto Belt. Duque-Caro (1979) had previously interpreted these onshore provinces and by extension the entire continental margin deformed belt to have been formed by compression normal to the Colombian coast, presumably during subduction of the Caribbean Plate beneath the south American Plate (Duque-Caro, 1979).

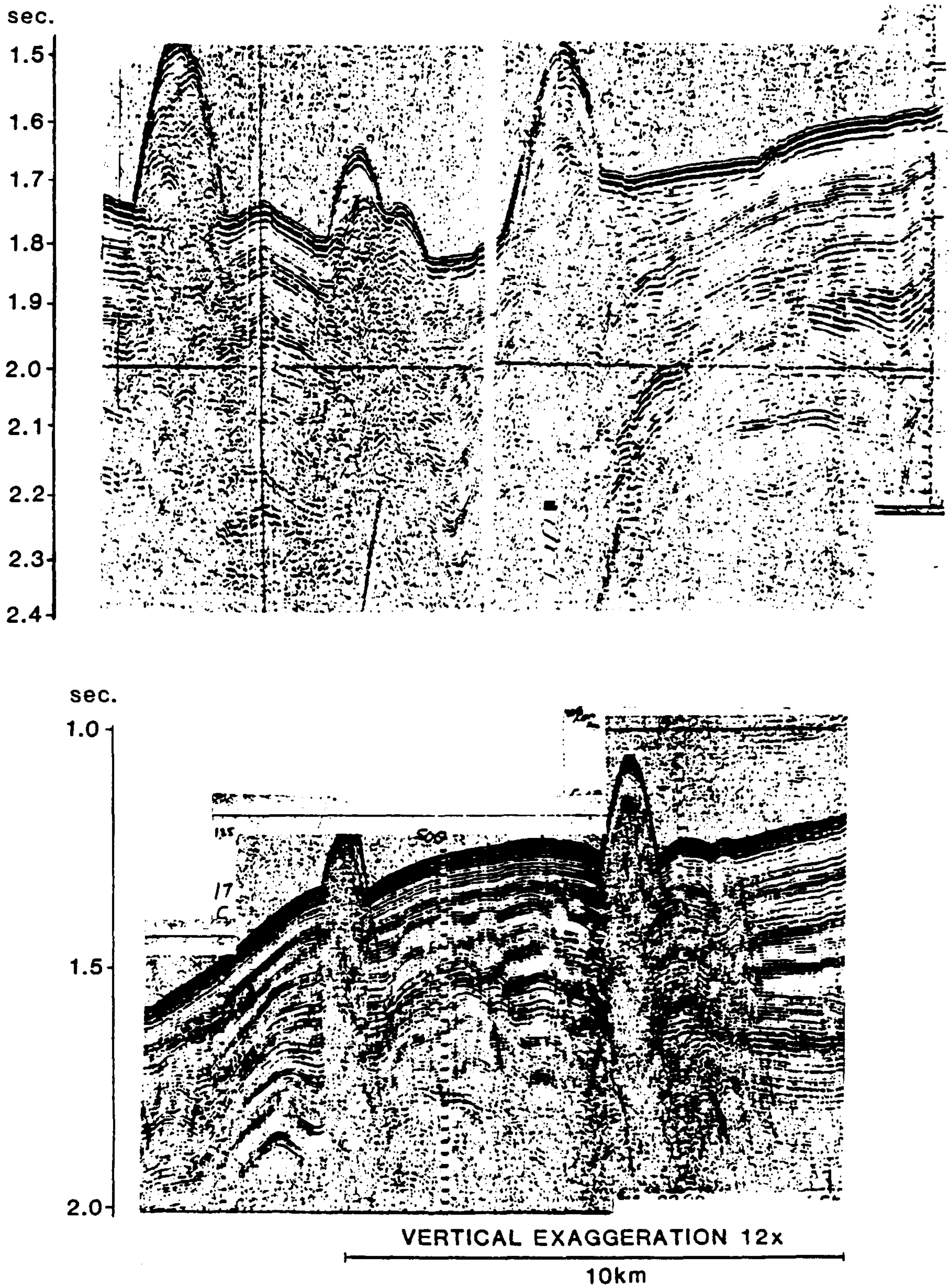


Figure 31. MUD DIAPIRS IN THE MAGDALENA FAN
After Sheperd et al., 1968

Further work (Duque-Caro, 1984) demonstrated that the onshore structures which had earlier been interpreted as typical compressional thrusts and folds displayed unusual features. The northeast trending fold structures were characterized by sharp, faulted anticlinal crests, and gentler, rounded synclines. The cores of the anticlines were composed of strongly disrupted pelagic and hemipelagic material. Capping these deposits much less deformed turbidites were found. Seismic expression of the anticlinal cores was chaotic with no visible internal structure which is similar to the typical response of mud diapirs from the Gulf of Mexico (Hedberg, 1980; Krason et al., 1986). Numerous conical hills composed of disoriented dried marine mud, probably extinct mud volcanoes, were located in the area. Active and dormant mud volcanoes abound in Duque-Caro's Sinu Belt, with principal concentrations along major northeast trending faults or lineaments.

Using these anomalous features of northwestern Colombia, Duque-Caro (1984) proposed that diapirism is the dominant deformational process and that compression from possible plate convergence had only a "minor contribution" to the process. He further claimed that multichannel seismic data from this area published by Lu and McMillen (1983) showed abundant diapirs on the continental slope. However, we suggest that the anticlines of the seismic sections from offshore deformed belt adjacent to northwest Colombia show significant stratigraphic detail within the cores of the anticlines, and as such do not strongly resemble the better documented mud diapirs of the western Gulf of Mexico. Furthermore, these sections do not display the sharp anticlinal crests and gentle, broad intervening synclines which Duque-Caro (1984) described on onshore mud diapirs.

Duque-Caro claimed that the intense diapirism which he documented was driven by the density difference between thick turbidites and underlying pelagites and hemipelagites. He presented no interpretation of why deeper, laterally continuous sediments should remain much less compacted than overlying sediments which are exposed to less overburden pressure.

Hedberg (1974, 1980) discussed Colombian mud diapirs and mud volcanoes in papers dealing with methane genration and hydrocarbon migration. Hedberg stated that a principal overlooked cause of overpressured, undercompacted shales was biogenic and thermogenic methane generation. Many of the accepted causes for overpressured intervals which had been proposed (e.g. pore fluid thermal expansion, montmorillonite dehydration, osmosis, etc.) only became potentially major formation pressure influencing factors upon very deep burial, 3,000 m or more. Hedberg noted that overpressured, undercompacted mobile shales are commonly expressed as shale (mud) diapirs and mud volcanoes along many continental margins, specifically citing Colombia, Trinidad, and the Makran coasts. Hedberg contended that if methane generation in a fine-grained sediment was sufficient to saturate the pore fluids and cause exsolution of gas as tiny dispersed bubbles, then many characteristic features of overpressured zones could be explained. Overpressured shales are known for their low seismic velocity, incoherent chaotic reflections, low thermal conductivity with concomitant high thermal gradients, high porosity, low density, and gravity anomaly lows. He further reasoned that methane generation would tend to plasticize and liquify shallowly buried non-lithified muds best; deeply buried shales are brittle and would tend to microfracture during hydrocarbon generation rather than become mobile (Tissot and Welte, 1978).

Hedberg's (1974, 1980) principal evidence for linking methanogenesis with mud diapirsm and volcanism is the profuse emanations of methane which have been recorded to accompany eruptions of mud volcanoes, particularly in Colombia. Hedberg (1980) showed photographs of vents from the Volcancitos and Turbaco areas of the Colombian coast which are actively bubbling methane gas, although he referenced no analytical results of the gas. Hedberg recounts a passage recorded in 1852 describing a mud volcano eruption along the Colombia. According to accounts by natives, the eruption was accompanied by a sequence of gas fires the last of which burned continuously for 11 days. Subsequently the mud volcano and peninsula upon which it was located subsided beneath the sea, but the gas continued to escape as a bubble plume to the surface. Hedberg (1980) stated that the outpouring of gas bubbles can still be noted at the site of the former mud volcano. Hedberg also noted a brief bulletin from a recent journal (Geotimes, 1976):

> "**Oct. 21** - Mud eruption and fire from La Lorenza, a vent about 70 km north of Monterila, Colombia; grey mud buried 2 houses and many farm animals; an hour later, methane gas from the vent ignited with a flame 100 m high and burned for several days, destroying houses and trees up to 8 km away. (La Lorenza is one of several vents in the area, a marshy region on the Caribbean coast. . .)"

The methanogenic origin of Colombian mud and shale diapirs is not entirely consistent with the field observations of Duque-Caro (1984). The onshore anticlines which Duque-Caro (1984) concluded to be diapirs are composed of very fine-grained pelagites and hemipelagites intruded into overlying turbidites. DSDP drilling has shown that the pelagic deposits of the Colombia Basin are exceedingly organic-lean, and thus presumably of low methane generating potential; whereas the only drilled turbidites are organic-rich (up to 7% TOC) and, in the hole nearest to the diapir field, Site 154, are very gassy.

There are possible ways around this incongruent situation of the sediments more likely to be gas generative (turbidites) being intruded by organic-lean pelagic and hemipelagic muds less prone to gas generation and thus undercompaction and diapiric flow. The deep sea sediments currently undergoing diapiric flow may not be directly correlative with those drilled in DSDP holes. No recoveries of slope apron or rise turbidites have been reported; they may be lean in organic matter. Conversely, pelagic sediments older than those sampled may have greater gas generative potential. The field evidence of turbidites underlain by disturbed hemipelagic sediments may be due to the diapirism itself rather than distinct lithologies. Duque-Caro's (1984) distinction of turbidites and hemipelagic/pelagic sediment was based principally on hand sample or outcrop recognition of graded bedding or the lack thereof. The diapirically mobilized hemipelagic/pelagic sediments may be distal turbidites, of proven gas generative potential, which were disrupted during intrusion sufficiently to destroy graded beds. That is, the hemipelagic/pelagic mobilized sediments of Duque-Caro (1984) may not be the same lithology considered by DSDP scientists to be hemipelagic/pelagic sediments. Another intriguing possibility is that the organic carbon content of the sediment does not always have a direct bearing on gas generation potential and thus propensity to be mobilized into a diapir. A review of work on the Gulf of Mexico by Krason et al. (1986, in press) showed that gas in amounts adequate for hydrate formation can probably be generated from sediments considered to be organically lean by conventional measures (0.3%). Another alternative interpretation is that thermogenic gas has migrated to the shale and mobilized it. Thus, the organic content of the mobilized shale would be immaterial, although no mechanism has been proposed in the literature for development of overpressurization by migration. No analyses of Colombian mud volcano gas or gas from nearby producing wells are available to determine its possible thermogenic origins. The predominance of gas shows and the lack of oil shows from commercial drill holes in the coastal area near the diapir fields (Colsa, 1982) suggests that the gas is from a biogenic or an extremely deep thermogenic source.

PART II

FORMATION AND STABILITY OF GAS HYDRATES

Selection of the Colombia Basin by DOE-METC as a site for the study of geological controls on gas hydrate formation and stability was based on published seismic evidence. Shipley et al. (1979) reported but did not publish seismic sections with bottom simulating reflectors from two sites in the southwestern Caribbean region. Lu and McMillen (1983) presented two seismic sections from the continental slope north of Panama and Colombia which displayed well developed bottom simulating reflectors (BSRs). Subsequently, Ladd and Truchan (1983) and Ladd et al. (1984) published three seismic lines from a similar geological setting 350 km further to the northeast which also displayed BSRs.

In the course of this study we have identified possible BSRs on at least sixteen additional seismic lines and have established that sediments capable of being sources of gas for the projected gas hydrates exist in Tertiary turbidites of the Colombia Basin.

In this section of the report we examine the relationships between the previously discussed geological conditions and history of the study region and gas hydrate potential are examined. The areal distribution and depth of the observed BSRs is examined in the context of the prevailing structural style of the survey sites. Factors determining the relative potential of thermogenic vs. biogenic hydrate development are discussed. The scant data available on the properties of the water and sediment columns which may potentially affect gas hydrate formation are summarized. These factors are then evaluated to rank the different areas of the study region as to gas hydrate potential and to provide an assessment of estimated volumes of natural gas trapped in and by gas hydrates.

Seismic Evidence

The Colombia Basin study region has been well surveyed by seismic reflection profiling. Seismic lines representing over 60,000 km of surveys were examined for BSRs. The majority of the seismic data are very poor quality, shallow penetration single channel lines produced with an air gun as a sound source. The majority of the few high quality multichannel lines available for the study area show BSRs. BSRs were found on the single channel seismic lines from only two of the 27 cruises for which data are available.

Multichannel Seismic Lines

The deformed belts which comprise the continental slope and rise north of Panama and Colombia have been surveyed using multichannel seismic profiling. Two sections from a set of proprietary data collected by the University of Texas Institute for Geophysics were published by Lu and McMillen (1983). Each of the lines, CT1-21 and CT1-25, shows prominent BSRs.

Section CT1-21 shows a well defined accretionary wedge and forearc basin both underlain by an unusually continuous BSR (Figure 32). The section is from off the north coast of Panama (Figure 17). The seismic line trends northwest crossing the west-northwest to west trending deformed belt at an oblique angle. The structure revealed by the section shows features of typical convergent plate boundaries. The undeformed basin sediments are juxtaposed against a complexly faulted and folded accretionary wedge composed of sediment blocks scraped from the impinging ocean floor. The imbricate faulting results in a structural high, which acts to pond terrestrial sediments landward forming a forearc basin. Compressional folds beneath the sediment-smoothed forearc basin are revealed by the deep penetration seismic section. The accretionary wedge structure is slightly different than that usually encountered along typical subduction zones in that its foot consists of a gentle fold rather than a sharp thrust fault. Also, the thrust faults of the accretionary wedge dip both landward and seaward rather than only landward as in the classical model. The typical basin floor type stratigraphy, marked by the distinct double band of discontinuous hummocky reflectors as discussed in a previous section, dips landward beneath the accretionary wedge. An unusually thick wedge of turbidites progrades outward from the foot of the slope filling the trench which is typically found at the foot of accretionary wedges. These irregularities may indicate that present movement is not purely compressional.

The BSR in section CT1-21 is remarkable in its extent, continuity, and high reflectivity. The BSR can be traced from the forearc basin to near the foot of the accretionary wedge for a distance of 120 km with only a few breaks in continuity, each of less than 3 km. The BSR is a very bold reflector, its reflection far more pronounced than any sedimentary horizon except for the sea bottom reflector. The BSR has the morphology which is typical of BSRs reviewed from other parts of the world; the topography of the sea floor is generally followed, but the BSR relief is more subdued. The BSR is deeper subbottom over rises than it is over depressions. This is entirely in accordance with the vertical fluctuation expected of a thermally controlled boundary such as the bottom surface of a hydrate stability zone. A BSR is expected to conform to geoisotherms which tend to be relatively depressed under rises and elevated under depressions due to the greater surface area and thus greater heat dispersing capability of a rise in contrast to a flat planar surface; the opposite effect prevails in the case of a depression. Lu and McMillen (1983) interpreted the BSR to continue shoreward from the forearc basin to the edge of the seismic section where the water depth is approximately 70 m. We suggest that the BSR cannot be traced with confidence shoreward of the forearc basin and becomes indistinct two-thirds of the way up the forearc basin slope, 10 km seaward of the slope break marking the transition of the forearc basin to the inner continental slope. We do not continue the BSR landward of shot point 280 (1,630 m

FIGURE 32, Seismic Section CT1-21, Offshore Panama, is located in the pocket at the end of the report.

water depth) because the reflector changes character, undulating in a manner which does not follow the expected geoisothermal form; in shallow water the reflector which Lu and McMillen (1983) interpret as a BSR shows more local relief (i.e. is "rougher") than the sea floor. The prominent reflector under the inner slope and shelf appears to be similar to inner slope unconformities identified elsewhere on the deformed belts by Shepard (1973) and Ladd et al. (1984).

Since gas hydrate stability is favored by increasing pressure, BSRs are expected to be found more deeply subbottom as they are traced seaward under progressively deeper water (Shipley et al., 1979). The BSR on line CT1-21 does not display such a relationship. A least squares correlation of BSR depth and water depth measured at 45 points along line CT1-21 showed no correlation; the Pearsons rho coefficient (r) of less than 0.07 was obtained. The greatest subbottom depth at which a BSR is found (0.60 0.62 sec) is at its nearest approach to shore, beneath the forearc basin. Conversely in the deeper water of the accretionary wedge, the BSR is significantly shallower (0.43 - 0.57 sec). One apparent explanation for this observation is that the change in depth of a BSR expected from a water depth increase from 1,850 to 3,000 m is small, but the BSR depth in sediment is very sensitive to changes in thermal gradient. Thus an increase in thermal gradient in the accretionary wedge complex may destabilize hydrate formation to the extent that the expected trend of a BSR becoming deeper in the sedimentary pile with increasing water depth is not manifested. The trend may be overprinted by the destabilizing effect of the possibly increased geothermal gradient of the accretionary wedge. Possible causes of this steeper geothermal gradient could include shale diapirism in the wedge, hydrothermal circulation in the disturbed section, or less compacted (more porous) accreted sediments. It is possible that the apparent depth to BSR is not strictly thermally controlled, but may be due to a difference in seismic velocity of the upper few hundred meters of sediments between the forearc basin and the accretionary wedge. Higher velocities in the sediments of the accretionary wedge due to a greater degree of lithification or more developed interstitial gas hydrates could produce a BSR which is apparently shallower in a seismic time section than a BSR at an identical depth beneath forearc basin sediments with a lesser degree of lithification and/or gas hydrate development.

The sediments above the BSR in section CT1-21 are much more acoustically transparent than those below the BSR. This seismic feature has been reported by Shipley et al. (1979) above BSRs from the Blake Outer Ridge and from the Pacific continental margin of southern Panama. Shipley et al. (1979) conjectured that the lower amplitude of reflections above the BSR may result from high velocity interstitial hydrates reducing the impedance contrasts between sedimentary layers and causing them to exhibit features of a more isotropic section. If such is the case, then the interstitial hydrates would appear to extend to within 0.1 sec (100 m) of the sea floor. The sediments above the BSR are most transparent along the structural high in the accretionary prism seaward of the forearc basin. This zone of maximum transparency corresponds with part of the section where the BSR is anomalously shallow (0.43 sec mean) and pronounced. This coincidence of shallow BSR and very transparent sediments would be consistent with the contention of Shipley et al. (1979) in that the interstitial hydrates possibly responsible for masking impedence contrasts and thus producing more transparent section may also raise the mean seismic velocity of the section.

This would make the BSR appear shallower in a seismic time section. However, Shipley et al. (1979) noted no major velocity anomaly in the hydrated section. It is also very possible that the apparent transparency results from some type of destructive reverberatory interference due to the high reflectivity and negative polarity of the BSR. However, one would then expect a similar effect above the water bottom multiple, another highly reflective negative polarity reflector. No such effect was seen on this or any other section.

Based on the previously discussed seismic stratigraphic interpretation of this part of the Colombia Basin, the sediments above the BSR on section CT1-21 appear to be of Pliocene and younger age.

Shipley et al. (1979) also referred to a section offshore of Colombia as exhibiting a BSR. The generalized location map of Shipley et al. (1979) indicates that the section is the same as that presented by Lu and McMillen (1983), CT1-25 (Figure 33). Section CT1-25 trends northwest, almost normal to the trend of the South Caribbean Deformed Belt offshore of northwestern Colombia (Figure 17).

The margin as pictured by CT1-25 is considerably different from the Panamanian margin seen in line CT1-21. Section CT1-25 shows a wider continental shelf; a narrower, less developed forearc basin, and a steeper accretionary complex which is less complexly deformed. The shelf portion of the section shows distinctly layered surface sediments becoming increasingly folded with depth. Some steep landward dipping reflectors can be noted between 2 and 5 travel time beneath the central part of the shelf. At the same depths near the left edge of the section (shot points (6,554 - 6,600) and beneath the shelf slope break (6,760 - 6,800) only chaotic reflectors are found, possibly indicating overpressured shale sections. Numerous anticlines are seen beneath the poorly defined forearc basin and the accretionary wedge. Although these structures may be cored by shale diapirs as suggested by Duque-Caro (1984), continuous arched sedimentary reflectors in the anticlines show that if the anticlines are diapiric in origin, the hypothesized mobilized shale does not extend upward into the gas hydrate formation zone. Thrust faults, concentrated on the lower slope can be traced on the section. The lowermost fault block is bounded by downward convergence of thrust faults and possesses a central synclinal fold. Lu and McMillen (1983) noted its resemblance to a positive "flower structure" as described in deep seismic sections by Harding and Lowell (1979). Positive flower structures are typically interpreted as resulting from oblique reverse faulting, i.e. combination of reverse and strike-slip motion. No published examples of flower structures illustrate such recent movement with great surface relief (300 m). The resemblance may be coincidental.

The sediments which are portrayed on the section are dominantly turbidites from the Magdalena delta and locally from the margin itself. The reflectors of the lower slope fault blocks and the adjacent abyssal plain are of the fan type stratigraphy as described by Lu and McMillen (1983).

A BSR can be traced from the foot of the continental slope to the juncture of the accretionary prism and forearc basin. The BSR on line CT1-25 is not of as high an amplitude as the BSR on line CT1-21. The BSR has two major breaks in continuity, the largest spanning about 4 km. The BSR does display the expected direct relation of depth in sediments to depth of overlying water, increasing from 0.37 sec subbottom at a water depth of 990 m to 0.60 sec subbottom under 3,000 m of water. A least squares correlation of BSR depth vs. water depth measured at 15 points along line

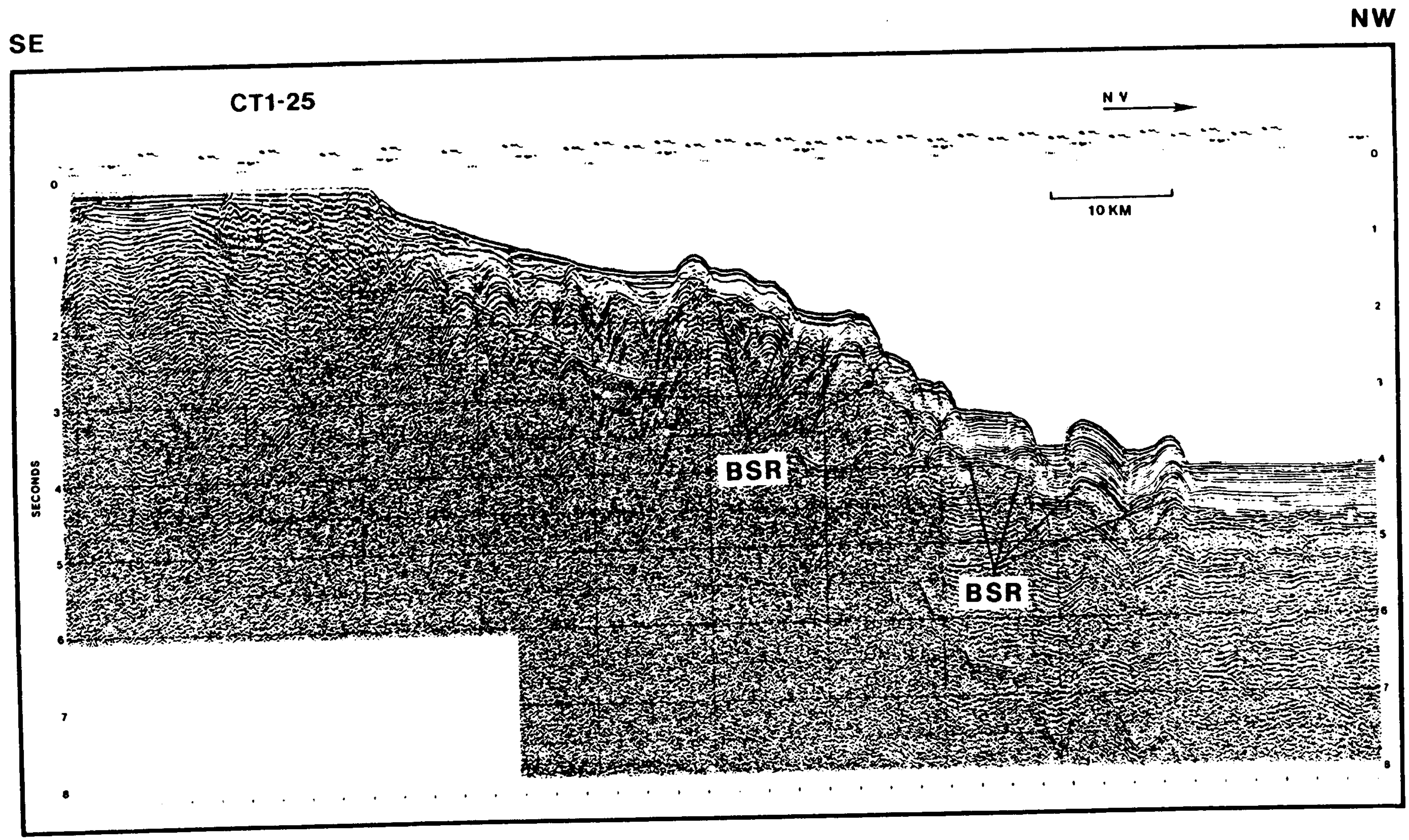


Figure 33. SEISMIC SECTION CT1-25, OFFSHORE COLOMBIA

After Lu and McMillen, 1983

CT1-25 yielded a very high correlation coefficient, r = 0.903. Some increase in acoustic transparency of the sediments above the BSR is evident. Once again, the greatest contrast in reflectivity between the strata above and beneath the BSR is near the structural high near the landward limit of the accretionary complex. The abyssal plain reflectors are approximately concordant with the sea floor which precludes tracing the possible BSR seaward of the deformed belt. However, the contrast in sediment reflectivity between the transparent upper section and a strongly reflective lower section can be noted paralleling the sea floor at 0.6 sec subbottom depth from the bounding thrust northwestward 15 km into the abyssal plain sediments. It may then be reasonable to infer a continuation of the BSR seaward for that distance although the hydrate reflector cannot be resolved from the strong concordant turbidite reflectors.

Other UTIG multichannel seismic lines and one LDGO line of the Colombian margin were published by Kolla et al. (1984). The lines from over the Magdalena Fan were discussed earlier (Figure 23) and show no evidence of BSRs. The sedimentary horizons on the Magdalena Fan are generally concordant with the sea floor at 0.3 to 0.7 sec depth range and thus hydrate horizons may be present but obscured.

One of the UTIG seismic lines reproduced by Kolla et al. (1984) was obtained from the Colombian margin southeast of the Magdalena Fan. Line CT1-27 (Figure 34) trends northwest subparallel to and 40 km from line CT1-25 (Figure 17). As expected, the structure and morphology of the margin on line CT1-27 closely resembles that of line CT1-25. The forearc basin is poorly developed. It is covered by a thin blanket of relatively transparent sediments. Sediment input to the forearc basin has been too slow to thoroughly smooth the sea floor; the sediments have been either thinly draped over existent anticlinal structures, deformed during deposition, or both. A distinct growth fault marks the right border of the section. The deformation of the accretionary prism appears to be dominantly landward dipping imbricate thrusts with associated drag anticlines. There is no direct evidence of diapirism in section CT1-27.

We propose that a faint discontinuous BSR can be seen in section CT1-27. The weak reflector is found at 0.52 sec subbottom at a water depth of 1,500 m. The reflector is similar in amplitude to bedding reflectors, but is discordant with them. The possible BSR can be traced with confidence for only 5 km, although faint, discontinuous reflectors in the proper depth range for gas hydrate boundaries can be located from the middle of the forearc basin to the foot of the accretionary prism, a distance of 30 km.

The difference in degree of BSR development on lines CT1-25 and CT1-27 is puzzling in view of their proximity and their similarity in structure, implied sedimentary makeup, and scale. Section CT1-25 displays a strong, continuous BSR, whereas the BSR on line CT1-27 is indistinct and discontinuous. The sediments which were accreted or underplated from the possibly subducting Caribbean plate should be similar in makeup; both are presented as type examples of fan type stratigraphy by Lu and McMillen (1983) and of lower fan-abyssal plain stratigraphy by Kolla et al. (1984). Being subparallel and located so close together normal to an essentially linear stretch of the margin would suggest that the compressive and/or shear forces which the margin experienced at each surveyed location would be very similar. The tectonic map of Case and Holcombe (1980) reveals few differences in

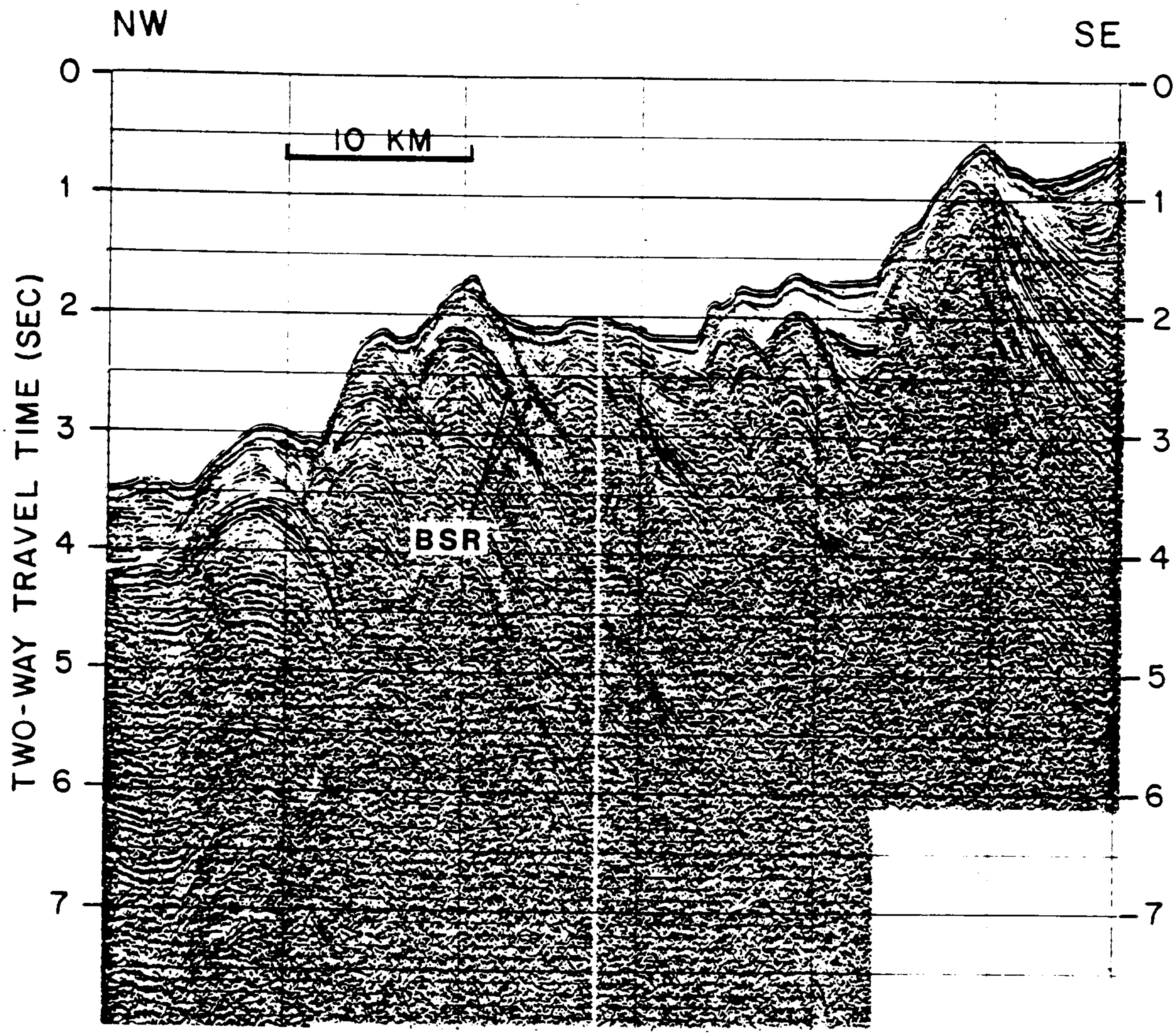


Figure 34. SEISMIC LINE CT1-27, CONTINENTAL SLOPE OFFSHORE COLOMBIA, SHOWING FAINT BSR OBLIQUE TO SEDIMENT REFLECTORS

After Kolla et al., 1984

structural style between the two sites. CT1-27 is closer to the source of the Colombia Basin turbidites, the Rio Magdalena. However this difference is expressed principally in the depth of the abyssal plain at the foot of the rise. No obvious geological differences between the locations of sections CT1-25 and CT1-27 can be found which could account for the dissimilarity in BSR development.

One possibly significant distinction between line CT1-25 and CT1-27 which is unrelated to the geology of the area is mentioned by Lu and McMillen (1983). These authors state that lines CT1-21 and CT1-25, each of which show strong BSRs, and CT1-22, which remains proprietary, were processed differently from the other seismic data of the CT1 series. These data from these three lines were subjected to migration using a wave equation algorithm to remove diffraction hyperbolae from the sections and improve resolution of deep structures. Shipley et al. (1979) published UTIG seismic sections with BSRs from a variety of geographic and geologic settings which had been processed using many combinations of processing options including filtering, gain recovery functions, deconvolution, and migration. However, the effect on BSR recognition of each processing operation, particularly migration, was not addressed. Previously, we had noted a different degree of BSR development in very closely spaced UTIG lines from the Gulf of Mexico which crossed the same structures but had been processed differently (Krason et al., 1986). In that case, migrated sections appeared to produce more recognizable BSRs. It is thus possible that the migration procedure used on lines CT1-21, CT1-22, and CT1-25 produced more visible BSRs than on the only nearby nonproprietary line which was not migrated, CT1-27.

Two other multichannel seismic lines from the South Caribbean Deformed Belt southeast of the Magdalena delta were published by Lehner et al. (1983). These sections, 1412 and 1413, were provided by Shell Internationale Petroleum Maatschappij B.V. and are located southeast of lines CT1-25 and CT1-27 (Figure 17). Line 1413, located 30 km from CT1-25 displays no BSRs. The published section of line 1413 only includes the shelf, inner slope, forearc basin, and only the most landward part of the accretionary wedge down to a water depth of 1,500 m. Typical imbricate thrusts are found in the section to the most seaward point surveyed. The adjacent line CT1-25 showed a strong BSR from an ocean depth of 1,000 m to 2,800 m. It is possible that BSRs are found in the deeper sections of the line which were not illustrated. The BSR on line CT1-27 only became evident under the second anticline/thrust structure seaward of the forearc basin, whereas line 1413 ends just seaward of the second anticline/thrust structure out from the forearc basin. Thus, much of the part of the slope which is structurally analogous to the portion of line CT1-25 underlain by a BSR is not pictured in line 1413. Line 1413 which displayed no BSR was not migrated during processing.

Further southwest along the Colombia margin, line 1412 shows what we interpret to be a BSR (Figure 35). The section shows the typical convergent margin structural features, but diffractions partially obscure the thrust planes and drag fold anticlines of the imbricate wedge. The BSR is continuous for 5 km along the section. The BSR varies from 0.54 to 0.65 sec subbottom and has the expected subdued response to topographic fluctuations.

One other UTIG seismic line is available from the North Panama Deformed Belt in addition to CT1-21. Line PN-1 is in the public domain but

FIGURE 35, Seismic Line 1412, Offshore Colombia, Showing Possible BSR, is located in the pocket at the end of the report.

has not yet been published. Line PN-1 trends northwest approximately normal to the margin of northwestern Panama (Figure 17). The line is approximately parallel to and 20 km southwest from the left lateral strike slip fault beneath the Panama Canal (Case and Holcombe, 1980). The structure revealed along line PN-1 (Figure 36) is apparently a convergent complex, but the usual sequence of the marginal structure of an accretionary prism, forearc basin, inner slope, and shelf is not readily discerned. The structure appears to be dominated with deep imbricate thrust faults. The drag folds of the thrust sheets are expressed at the sea floor as anticlines. Little sediment ponding can be noted, consistent with the lack of a major terrestrial sediment source landward of the section. The details of the structure are not easily resolved; PN-1 was not migrated during processing and thus abundant diffraction features overwhelm the deep stratal reflectors.

A moderately reflective BSR appears on Line PN-1 (Figure 36). The BSR can be traced 60 km along the section, but it is not continuous along the entire distance. Breaks of as much as 2 km are seen along the BSR. The BSR ranges from 0.40 to 0.48 sec subbottom depth, generally trending deeper in the sediments as the water depth increases from 1,600 m to 2,600 m. A least squares correlation of BSR depth in sediment vs. water depth yielded a moderately good correspondence with a Pearsons rho value (r) of 0.68. The BSR is approximately as reflective as the strongest sedimentary layer but more reflective than typical sedimentary layers. The BSR is bolder and more continuous over anticlinal structures including the thrust sheet drag folds. Some diminution of seismic returns above the BSR is noted. Widely spaced strong reflectors are present in this zone of relative transparency. Weaker returns are attenuated above the BSR. The degree of acoustic transparency is less than in either CT1-21 or CT1-25.

One UTIG multichannel seismic line from the abyssal plain of the southwestern Colombia Basin may show a BSR over a faulted ridge. Line CT1-12 (Figure 29) trends northeast-southwest through the southwestern Colombia Basin approximately paralleling the Hess Escarpment (Figure 17). Line CT1-12 was discussed earlier in the seismic stratigraphy section of this report. Line CT1-12 crosses structures which can be correlated with those upon which DSDP Sites 154 and 502 were drilled. The only copy of line CT1-12 that has been publicly released is a small, poor quality section (Figure 29) published by Lu and McMillen (1983). Although it cannot be verified using this poor reproduction, a BSR may exist on the small faulted ridge which was correlated to Site 154. The ridge with the highest relief of the three small fault blocks between shot points 7,000 and 7,200 has a strong reflector at 0.45 sec subbottom which crosses sedimentary horizons. This prominent reflector cannot be traced with certainty away from the ridge as would be expected if it were a sedimentary horizon. The reflector is similar in appearance to the BSR on line CT1-21; both are composed of two very high amplitude reflectors separated by 0.02 sec. There is an increase in acoustic transparency above the possible BSR, but that also may be attributed to a more pelagic sediment type above the reflector. If this unusual reflector is a BSR, increased acoustic transparency may help explain why the expected turbidite horizon at 0.2 sec subbottom could not be resolved.

Drilling results suggest that a BSR might be expected along this ridge. Very gassy sediments were drilled at Site 154, 50 km southeast of the line, but the hole was terminated 300 m above the depth of the possible BSR seen on line CT1-12.

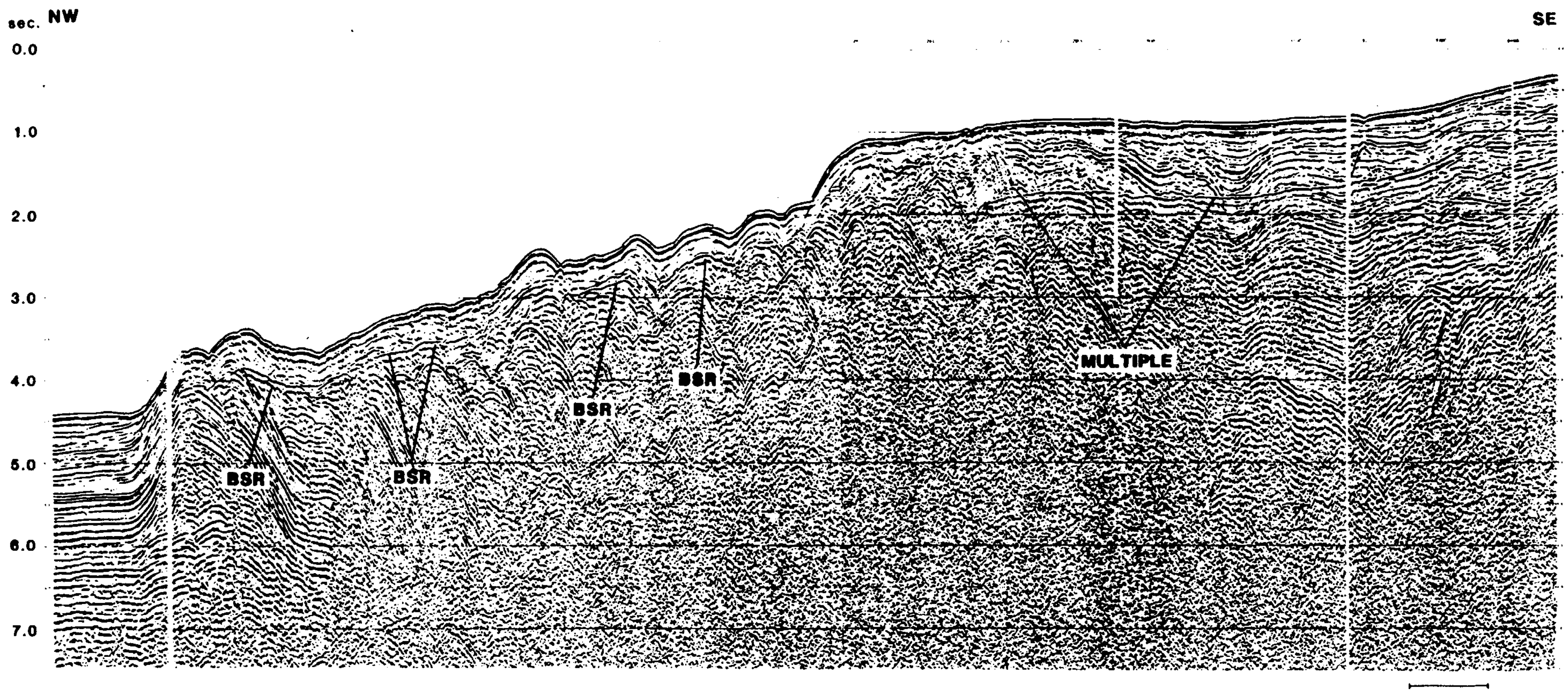


Figure 36. SEISMIC LINE PN-I, NORTH PANAMA DEFORMED BELT

After unpublished data from the University of Texas Institute for Geophysics, 1985

Three LDGO multichannel seismic lines from the continental margin of northeastern Colombia were reproduced in articles by Kellogg and Bonini (1981), Ladd and Truchan (1983), and Ladd et al. (1984). BSRs were marked on the sections by Ladd and Truchan (1983) and Ladd et al. (1984).

Seismic line 129 (Figure 24) runs north-northwest offshore of the Sierra de Santa Marta 100 km northeast of the outlet of the Rio Magdalena (Figure 17). The seismic line crosses the Aguja Canyon obliquely at shot point 680 and cuts through an outside bend in the canyon at shot point 190. The section shows syndepositional folding of a thick drape of turbidites. The foot of the continental rise shows an obvious thrust fault with apparent slumping of slope material prograding over the abyssal plain. As mapped by Shepard (1973) this section of the Aguja Canyon traces a generally northwest trending zig-zag pattern alternating in course from north-south to east-west in 20 km segments. This is suggestive of lateral offset of drainage commonly noted at onshore strike-slip fault traces. Thus the east-west segment crossed by line 129 may be a strike-slip fault zone. There exists a stratal discontinuity beneath the canyon on line 129 which may be due to faulting. However, the movement necessary to produce the observed zig-zag of the Aguja Canyon would be left-lateral, opposite of the prevailing style in this part of the margin (Case and Holcombe, 1980).

The BSR on line 129 is faint. The BSR noted by Ladd et al. (1984) consists of two segments each 1 km across. The BSR is seen cutting across a pair of anticlines at 0.6 sec subbottom. A more subtle trace can be picked out on the landward wall of the Aguja Canyon at 0.5 sec subbottom and extending 2.5 km. In a print of the same section in a more horizontally compressed format presented by Kellogg and Bonini (1981) the BSR can be seen to be weak but detectable from the pair of anticlines noted by Ladd et al. (1984), through the intervening syncline to the foot of the slope at the junction with the abyssal plain. Thus, a lateral extent of 20 km and possibly as much as 25 km is inferred for the BSR on line 129. There is no indication of the BSR continuing shoreward of shot point 600, but the sea floor and strata are conformable in that stretch, which may obscure any gas hydrate reflection. A very slight increase in acoustic transparency above the BSR is noted in line 129, but only where the BSR is most reflective.

Seismic line 130 shows a very well developed convergent margin structural complex comprising an accretionary prism with a structural high and a forearc basin which merges landward with the inner continental slope (Figure 25). Line 130 trends west-northwest 100 km northeast of line 129 (Figure 17). Landward dipping thrust faults in the accretionary wedge are particularly well defined in this section. The Rancheria Basin, a very large forearc basin, covers over 3,000 km^2. The forearc basins seen in other seismic sections from along the Caribbean margin are typically much less obvious, occasionally being marked by only a mild slope break. Mann and Burke (1984) proposed that the Rancheria Basin is also genetically dissimilar from other local forearc basins. Mann and Burke (1984) classify the Rancheria Basin as a "pull apart" basin resulting from an underlying north-south offset of an undetected east to west trending right lateral strike-slip fault. We have seen no seismic evidence from the Rancheria Basin which would support or refute such an interpretation.

A discontinuous BSR is seen on line 130 in the accretionary prism and part of the forearc basin (Figure 25). The BSR varies in depth from 0.55 to 0.70 sec subbottom. The BSR on the slope is very reflective at five points and is absent or much less reflective between. These most reflective segments of the BSR appear to be concentrated over or just seaward of major thrust faults. This suggests that gas migration along thrust faults or local gas mobilization in fractures in fault zones and associated drag folds may be operating to enhance gas hydrate development. The BSR can be recognized at the base of the continental slope, merging with a strong abyssal turbidite reflector seaward. The trace of the BSR can be detected continuing from the accretionary wedge into the undeformed sediments of the Rancheria Basin. The BSR continues at least 5 km shoreward beneath the Rancheria Basin. At approximately shot point 4,080, the BSR merges with a bold reflector which Ladd et al. (1984) interpreted as an unconformity (Figure 25). Within the resolution of the published sections it is possible to trace some landward dipping sedimentary reflectors through this unconformity. This may only be an apparent continuity of beds above and below the unconformity; the attitude and character of these sediments may be too similar to be differentiated with the seismic methods. If the continuity of beds above and below the labeled unconformity is real then the reflector may be a diagenetic boundary. There is a slim possibility that the shallow unconformity labeled in Figure 25 is the continuation of the BSR which would explain the relatively transparent. nature of the sediments above this horizon. The major impediment to interpreting the horizon as a landward extension of the BSR is that the reflector plunges in subbottom depth along the section reaching a depth of 0.9 sec at shot point 4,450. The extreme difference between the 0.6 sec BSR depth on the accretionary prism and the 0.9 sec in the forearc basin could conceivably be caused by (1) anomalously porous or undercompacted sediments, resulting in low seismic velocity for the section, and/or (2) anomolously low geothermal gradient or anomalously high pressure gradient resulting in a deeper hydrate stability zone. A similar situation of a landward deepening BSR in a forearc basin was previously discussed; the BSR on line CT1-21 (Figure 32), the only other section encountered with such large and well defined forearc basin, plunged from 0.5 sec to 0.65 sec at its point of disappearance. However the 0.65 sec subbottom BSR depth in the forearc basin of line CT1-21 is well within the range of depths observed for BSRs worldwide; the 0.9 sec depth incurred if the unconformity on line 130 is interpreted as a BSR is deeper than any reported BSR.

The BSR on line 130 is continuous for 40 km with decidedly variable reflection amplitude along its trace. The BSR continues for at least 5 km beneath the forearc basin.

LDGO seismic line 132 (Figure 26) crosses the continental slope in a north-northeast direction north of the Guajira Peninsula of northeastern Colombia (Figure 17). Line 132 is located 160 km northeast of line 130. Line 132 is landward of the Aruba Gap but the published section does not extend to the abyssal plain of the Aruba Gap. The seismic line shows a broad but still highly deformed accretionary wedge and a forearc basin which is less defined than the Rancheria Basin. A thick sediment pile is draped over the accretionary complex showing evidence of syndepositional compressional deformation.

A BSR can be traced on line 132 (Figure 26) for over 70 km. The BSR ranges in depth between 0.57 and 0.65 sec subbottom. From the left side of section to shot point 1,800, the BSR is very reflective and continuous. Landward the BSR becomes much less continuous and varies in amplitude. The BSR continues into the forearc basin for a distance of less than 10km.

In contrast to lines CT1-21 and 130, the BSR attains a shallower subbottom depth as it passes landward beneath the forearc basin. The thickness of the prograding sediment over the accretionary wedge hinders interpretation of the style of deformation and thus precludes a correlation of the most reflective BSR segments with particular structural features. An increase in acoustical transparency above the BSR is evident on line 132.

A multichannel seismic section of the South Caribbean Deformed Belt north of the Guajira peninsula was published by Lehner et al. (1983). Line 1422 (Figure 37) is located 40 km west of and parallel to line 132 (Figure 17). Unlike line 132, line 1422 illustrates the sediment layers beneath the deep abyssal plain of the Aruba Gap. The line crosses the Aruba Gap and the rise which borders the north flank of the gap marking the beginning of the transition to the Beata Ridge, and continues to intersect DSDP Site 153. The reflection configuration agrees well with the drilling results; 0.6 second transparent section corresponds to the 700 m of pelagic carbonates drilled. The layered reflectors beneath 0.6 seconds subbottom depth at Site 153 should represent the carbon-rich (up to 6.2% T.O.C.) shales and turbidites floored by basalt.

Seismic line 1422 (Figure 37) illustrates graphically the structural control on sedimentation of the pelagic carbonates which are essentially barren of organic matter at Site 153. The turbidite layers immediately above the very strong reflectors representing basalt/diabase flows and sills (reflector B") can be traced through the Aruba Gap, over the faulted, uplifted block and to DSDP Site 153. This suggests that before the uplift of the large faulted block upon which Site 153 is found, the entire abyssal area pictured received terrestrial, probably organic-rich sediments. The uplift of the east-west trending ridge between shot points 1,150 and 1,225 introduced a topographic barrier which blocked turbidity currents from the Colombia continental margin from reaching the area of Site 153. In the absence of deposition of voluminous turbidites directly from the continental margin and from the Magdalena fan via downslope transport from the Colombia Basin to the Venezuela Basin, only slow pelagic sedimentation occurred on the rise upon which Site 153 is situated. Seismic stratigraphic reconstruction of this section using the assumptions of Hopkins (1973) shows that: (1) the organic rich turbidites and clays should be within the gas hydrate stability zone over the ridge and (2) these same sediments when correlated to the foot of the continental slope are covered by 2 sec (about 2,200 m) of turbidites which may be sufficient to initiate thermogenic gas generation for eventual migration upwards into the gas hydrate stability zone. The structure of the continental margin is obscured by diffraction reflections. By comparison with other nearby lines with better resolution of margin structures, it is reasonable to infer imbricate thrusts grading landward to compressional folds.

Although Lehner et al. (1983) did not mention BSRs on line 1422, we have identified a reflector on line 1422 which we interpret to be a BSR (Figure 37). The BSR continues from shot point 1,030 at the foot of the continental slope to at least shot point 940 within the accretionary prism. A strong discordant reflector appears at shot point 918 and continues landward to the left edge of the section and presumably beyond. A continuous BSR extent of over 30 km beneath the lower reaches of the margin and at least 7 km on the upper reaches near the edge of the section 1422 is thus estimated. The BSR is found at between 0.55 and 0.68 sec subbottom with the typical pattern of being deeper in the sediments above antiformal areas than beneath

FIGURE 37, Seismic Section 1422, Aruba Gap Showing BSRs, is located in the pocket at the end of the report.

synformal areas. There is a slight increase in acoustic transparency above the BSR which is most obviously displayed above the most seaward reaches of the BSR. The BSR may continue seaward beneath the turbidites of the Aruba Gap. The BSR merges with a strong turbidite reflector; the concordance of the abyssal sea floor and sediments does not allow the presence of the BSR to be determined positively or negatively.

One multichannel seismic line, B-3, presented by Hopkins (1973) covers the Aruba Gap approximately 15 km west of line 1422 (Figure 17). Line B-3 (Figure 38), which does not include any reflections of the continental margin, was published in a format which was highly compressed horizontally (V.E. = 1). This extreme vertical exaggeration serves to accentuate minor discordance between the sea floor and sedimentary horizons. Thus minor differences in reflector attitude which may indicate a gas hydrate horizon should be more visible in line B-3 than in line 1422 with a mild vertical exaggeration of 2x. A strong reflection which is discordant with bedding can be traced from shot point 950 to shot point 1,150 at 0.55 sec subbottom (Figure 38). This reflector could be interpreted as an unconformity; however, distinct beds can be traced through the reflector. Small faults which offset sediment layers do not offset this discordant reflector. Based on the subbottom depth, concordance with the sea floor, and evidence of conformable deposition above and below the reflector, we propose that the anomalous reflector be considered as a BSR in the same class as those documented on the nearby continental slope. The Aruba Gap near the path of line B-3 is highly faulted (Hopkins, 1973; Roemer et al., 1973; Case and Holcombe, 1980; Stoffa et al., 1981; Mann and Burke, 1984). This structural disturbance may have mobilized gas and produced more favorable conditions for gas hydrate formation than in typical abyssal plain environments.

Single Channel Seismic Lines

Single channel seismic lines tend to have poorer resolution of stratigraphic detail and much less penetration than multichannel processed seismic lines. However, much more single channel data are available for the Caribbean. All public domain single channel seismic profiles from the study region were examined for evidence of gas hydrates.

Previous work (Krason et al., 1986) has shown that single channel sparker seismic lines can resolve BSRs, occasionally better than multichannel processed data. On the other hand, single channel air gun seismic lines show universally poor resolution of hydrate boundaries. No high quality sparker lines could be identified for the Colombia Basin study region. Single channel air gun profiles were reviewed, but the resolution and depth of penetration were by and large too poor to indicate the presence or absence of BSRs with any certainty.

One exceptional set of single channel air gun seismic lines was taken during cruise 54, leg 3 of the R/V Atlantis II from the Woods Hole Oceanographic Institution (WHOI). These unpublished profiles cross the Caribbean continental margin 11 times in a zig-zag pattern from the Panama Canal to the Guajira Peninsula (Figure 17). The quality of these lines is occasionally sufficient to resolve sediment layers in the depth range expected for BSRs; such resolution is necessary to establish discordance which is a prime criterion of confident BSR detection. We have identified BSRs on eight of the 11 crossings of the marginal deformed belts (Figure 17). Equipment difficulties

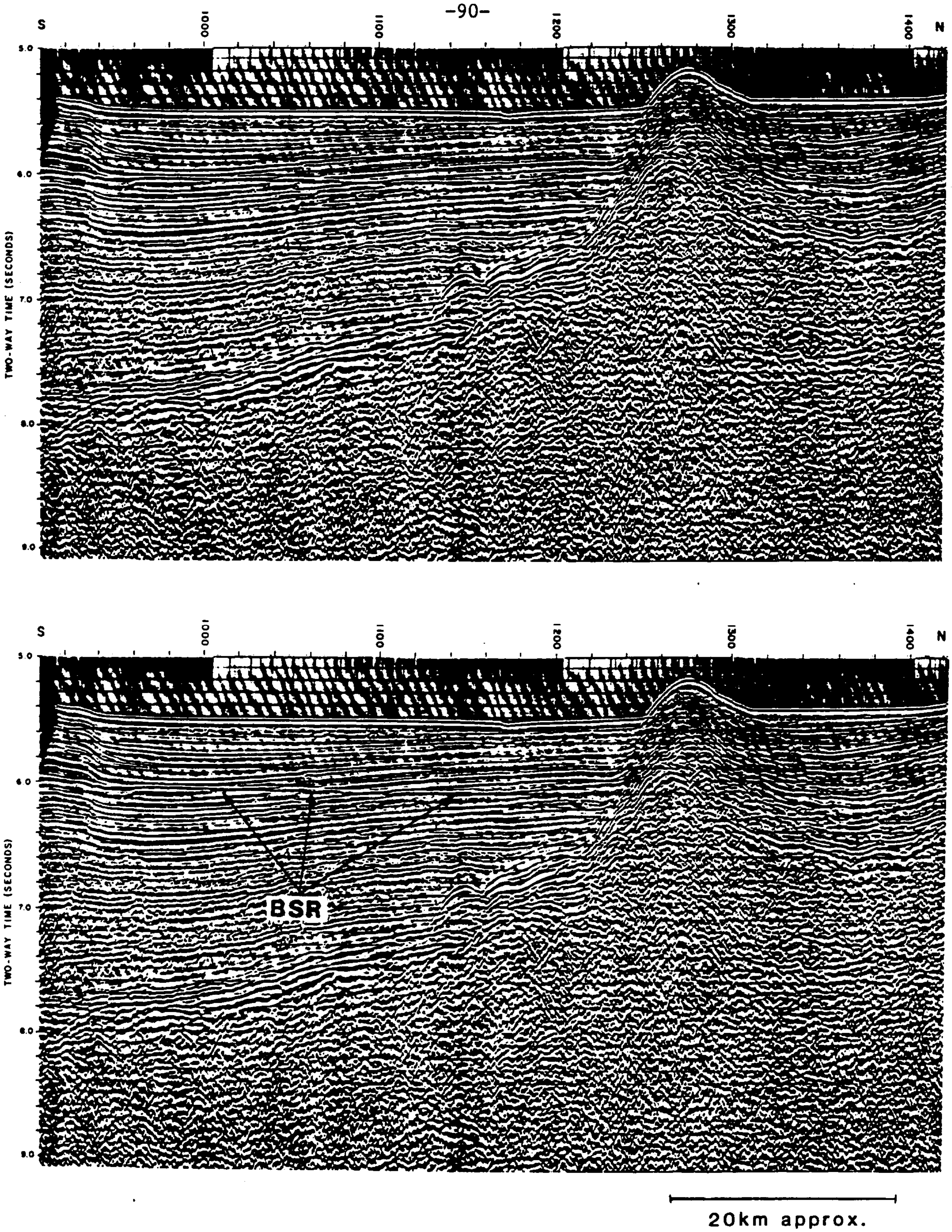


Figure 38. SEISMIC LINE B-3, ARUBA GAP SHOWING POSSIBLE BSR

After Hopkins, 1973

resulted in poor quality or no data recovery over some sections where hydrates may be expected based on previously examined multichannel evidence. Also, at times the depth of penetration was significantly diminished to less than the expected subbottom depth of gas hydrate horizons.

One particularly interesting seismic line from the 1969 Woods Hole cruise is from the North Panama Deformed Belt. WHOI line 54-3 parallels the multichannel line CT1-21, 20 km to the southeast (Figure 17). Line CT1-21 displays a highly reflective BSR from the forearc basin to the foot of the continental slope. The BSR on CT1-21 was most robust and anomalously shallow over the structural high seaward of the forearc basin. The BSR diminished somewhat midway down the slope and again became very reflective near the foot of the slope (Figure 32). On the parallel Woods Hole line (Figure 39) a similar pattern is seen, except that the BSR is much less easily recognized. However, for single channel air gun records, the BSRs on this section are indeed extraordinarily strong and persistent. Since the single channel trace along this line is so well defined we may then reasonably infer that the exceedingly reflective BSR on line CT1-21 is real and that the exceptional hydrate development or sub-hydrate gas trapping can be extended laterally at least 20 km. Further evidence for lateral extent of this prospective area remains scant; most of the remaining single channel tracks are not so fortuitously close to multichannel lines to permit direct correlation of BSRs. The two WHOI lines between lines PN-1 and CT1-21 do show BSRs, but they are not as distinct or continuous as those immediately adjacent to line CT1-21. Immediately offshore from the Panama Canal Zone the WHOI lines are plagued by insufficient depth of penetration to confirm BSR presence.

Farther east nearer the juncture of the North Panama Deformed Belt and the South Caribbean Deformed Belt, instrumental malfunction prevented surveying areas where hydrates would be expected. In the short segments where the instrument was functioning properly, short discontinuous BSRs are seen. This suggests that some BSRs may exist in the segments for which no records exist, but those BSRs are probably not as reflective or continuous as those near line CT1-21.

The track of the Atlantis II crossed the segment of line 1412 which we contend displays an unreported BSR (Figure 35). Unfortunately, the seismic instrument was not operating during the crossing which prevents independent confirmation of the proposed BSR on line 1412. However the seismic profiler was functioning shortly after the crossing of the path of line 1412 and operated continuously while on a course subparallel to and 20 km northeast of line 1413 (line 54-6, Figure 17). Distinct BSRs are seen in the WHOI line 54-6 at a structural position comparable to that on line 1412 where the proposed BSR was manifested (Figure 17).

Much of the next 900 km of seismic records of the WHOI cruise traverses the Magdalena Fan. No BSRs were noted on the fan. This is consistent with an absence of BSRs in multichannel lines CB-1 and 127 also collected over the fan.

Northeast of the Magdalena Fan the Atlantis II made 3 crossings of the deformed continental margin. No BSR was noted on the first two lines which surveyed fairly close to the Magdalena delta. Here the heavy sediment cover, although occasionally deformed, did not present the ideal geometrical situation to confirm BSR presence or absence. The WHOI cruise did cross the diapir fields mapped by Shepard (1973). A short anomalous reflector, possibly a BSR

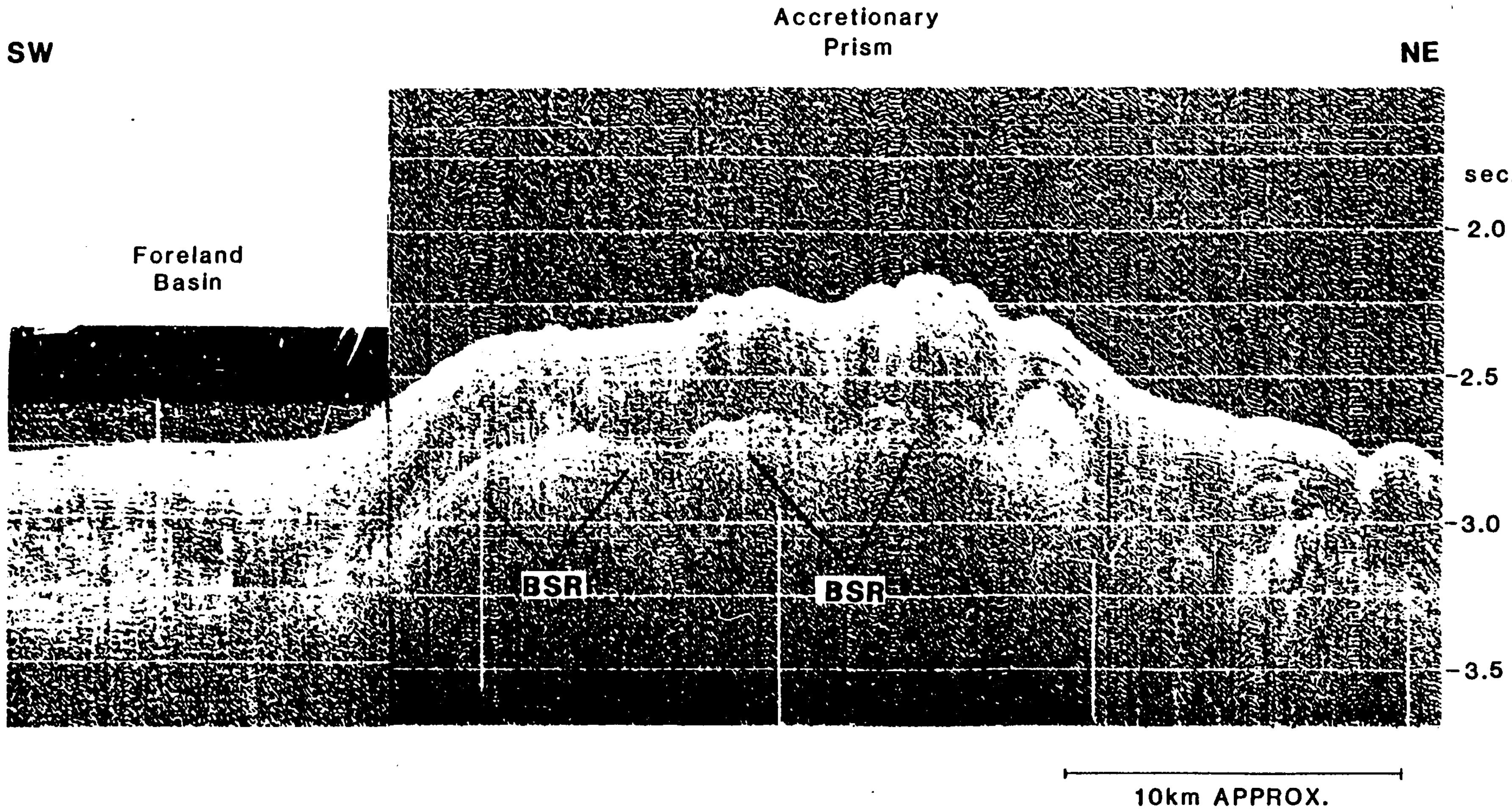


Figure 39. SEISMIC LINE 54-3, OFFSHORE PANAMA

After unpublished Woods Hole Oceanographic Institution data was found on the flank of a diapir at a water depth of 1,200 m (line 54-10, Figure 17). If this is indeed a hydrate horizon, Hedberg's (1980) view of mud diapirism resulting from methane generation would be supported. It is hardly surprising that no extensive BSRs were identified on these two lines. The high quality multichannel seismic line closest to these WHOI lines, LDGO line 129 (Figure 24), showed only a faint, discontinuous BSR of only 20 km extent.

The remaining WHOI line 54-11 crossed the continental margin close to the path of line 130, transecting the Rancheria Basin (Figure 17). On this line (Figure 40) a possible BSR can be traced for about 10 km from the first fold of the accretionary prism bordering the Rancheria Basin landward beneath the Rancheria Basin. The BSR is found at 0.67 sec subbottom on the accretionary wedge and dips to 0.72 sec subbottom beneath the forearc basin. The BSR reappears sporadically seaward beneath anticlines of the accretionary wedge and becomes indistinguishable beneath the turbidite reflectors of the Colombia Basin.

The single channel seismic data upon which the paper by Krause (1971) was based comprise closely spaced lines crossing the margin from the Magdalena delta to the Guajira Peninsula and extending across the Aruba Gap to the general vicinity of DSDP Site 153. No copies of these seismic lines from the 1966 voyage of the R/V Trident, Cruise 36 were presented by Krause (1971). Some generalized line drawings did indicate that the seismic sections had sufficient penetration to perhaps display BSRs. Unfortunately, most of the original seismic sections are not available for study, since only a few lines of the many which were taken in the area of interest could be located in the University of Rhode Island data archives. Once again, the quality and scope of the sections which were available for study varied greatly depending on instrument status. The survey was carried out with a battery of four air guns. When all were functioning the quality of the data were good; typically, however, fewer than the full compliment of sound sources were concurrently operational.

One line of acceptable quality crossing the accretionary prism has survived. Line TR-36-4 trends north-south over the landward side of the accretionary prism adjoining the Rancheria Basin (Figure 41). The short segment which is available crosses the Rancheria Basin approximately 40 km northeast of the WHOI line and 70 km northeast of LDGO line 132 (Figure 17).

A BSR crosses the folded accretionary section and can be traced intermittently beneath the Rancheria Basin. A syndepositional fold in the Rancheria Basin produces a discordant relationship between the sea floor and the sediment layers permitting detection of the BSR at 0.62 sec subbottom. This section exhibits the same structure to depth relationship seen in the other two sections from the Rancheria Basin (130 and WHOI-52-11); the BSR deepens from 0.51 sec on the accretionary wedge to 0.64 sec in the forearc basin.

The possible BSR found on multichannel seismic line B-3 (Figure 38) does not show up as well on a single channel trace from the same survey (Hopkins, 1973). A very faint reflection can be traced for 10 km at the same depth as the BSR on line B-3. This serves to illustrate the increased resolution of BSRs on multichannel seismic lines as opposed to single channel. The single channel version of line B-3 does tend to verify that the anomalous reflector

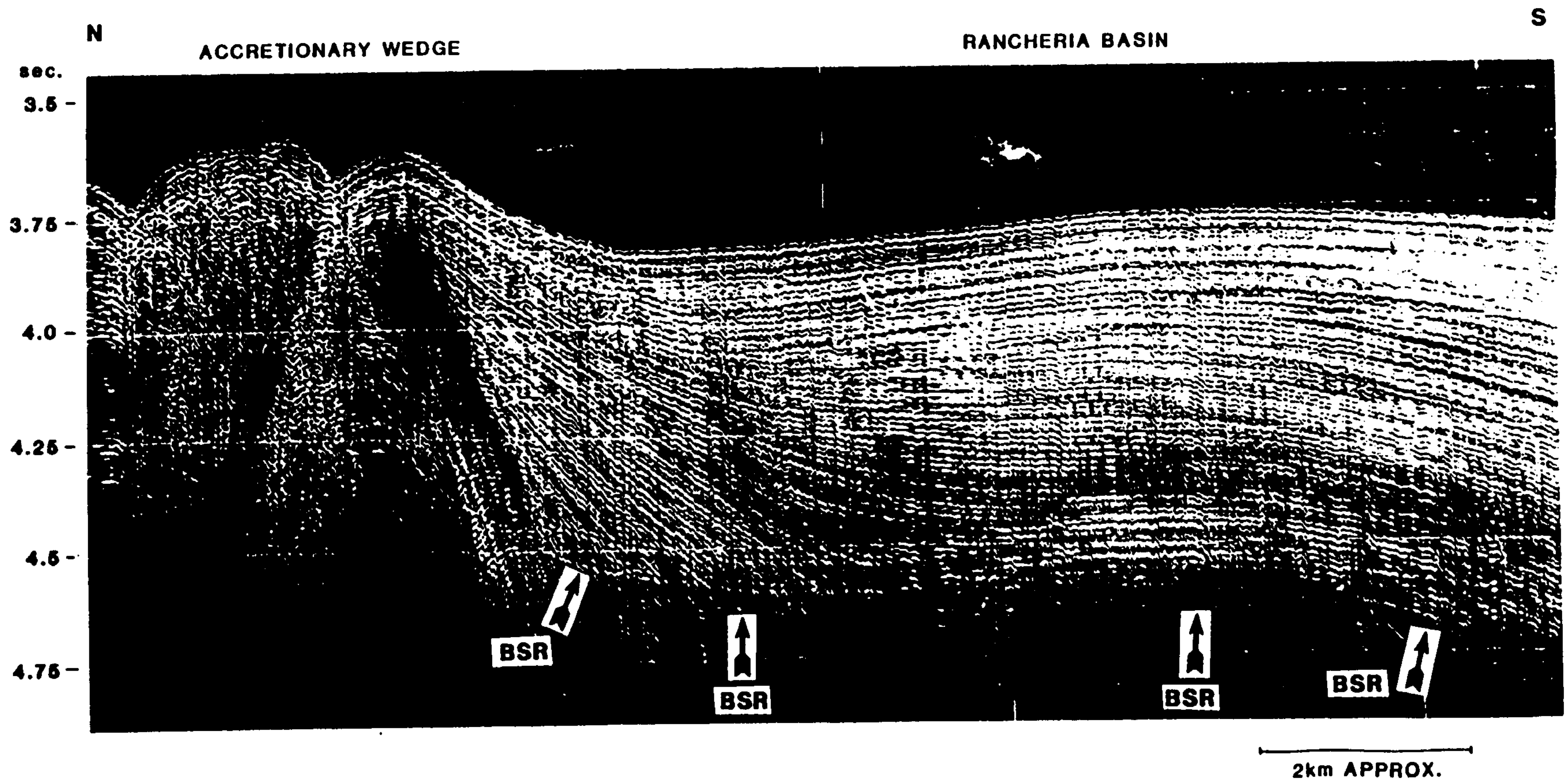


Figure 40. SEISMIC LINE 54-11

After unpublished data from Woods Hole Oceanographic Institution

FIGURE 41, Seismic Section TR-36-4, Showing BSRs, is located in the pocket at the end of the report.

on multichannel seismic line B-3 is indeed a BSR. Since the discordant reflector is less well developed on the single channel version, the discordant sedimentary layers are better resolved. The single channel section shows that the sedimentary layers are continuous in passing through the depth occupied by the BSR. Thus, the single channel seismic section shows that the most likely alternative to the anomalous reflector being a BSR, that it is an angular unconformity, is untenable.

Moore and Fahlquist (1976) presented a composite single channel seismic line which extended from the Colombia continental margin offshore from the Guajira Peninsula across the Aruba Gap and Beata Ridge to the Nicaragua Rise tying together DSDP Sites 151, 152, and 153. The published reproduction of the seismic section was not of sufficient quality or scale to distinguish BSRs. The authors did mention that there may be an unconformity in the turbidites of the Aruba Gap at 0.5 sec subbottom depth. The unconformity is not visible in the small illustration provided in the article. A slightly larger and better quality print of the same Texas A&M University seismic line is included in the work of Roemer et al. (1973). However the unconformity at 0.5 sec subbottom is not evident in the marginally better copy. This reported unconformity which we could not resolve in published examples may be a hydrate horizon. The BSR on line B-3 appeared to be an unconformity, but close inspection showed it to be something other than an unconformity; a similar situation may exist with the line described by Moore and Fahlquist (1976) and Roemer et al. (1973). The Texas A&M line passes 30 km east of line B-3. Since the BSR on line B-3 extends at least 35 km from north to south, it is not unreasonable that it may also exist 30 km to east.

Moore and Fahlquist (1976) mentioned unusual reflectors in the Colombia Basin between the Beata Ridge and the Nicaragua Rise. These reflectors "vary in acoustic response and stratigraphic position" and are found at 0.6 sec subbottom. The authors suggested that the reflectors may represent a gas hydrate zone. The quality of the seismic lines presented by Moore and Fahlquist and the duplicate seismic lines in the paper by Roemer et al. (1973) do not permit confident determination of the probable origin of these reflectors.

Drilling Evidence

There have been no reported recoveries of gas hydrates from sediment of the Colombia Basin study region. No holes have been drilled in sufficiently deep water over the deformed belts, shown by seismic surveys to be the most likely gas hydrate province. There has also been no drilling into the turbidites which cover the abyssal plain of the Colombia Basin.

All DSDP sites within the study region were purposely located in geological settings which are atypical of the study region as a whole. To obtain cores with abundant fossils for precise dating and to recover the greatest possible time equivalent of strata, only locations which received direct pelagic sedimentation were chosen for DSDP drilling. Thus, the five DSDP sites in the study region were all located on bathymetric highs, above the level of turbidity currents. The pelagic sediments cored were mainly carbonate muds which contained only minor amounts of organic carbon (0 - 0.2% TOC).

At three of the DSDP sites (151, 153, 154) sediments deposited prior to uplift of the sites to present position were recovered. The basin floor turbidites and hemipelagites cored at each site under the pelagic ooze contained abundant organic carbon (up to 6.2% TOC). By extension, organic-rich sediments which may serve as sources for gas hydrate methane would be expected over large areas of the basin.

At DSDP Site 154 biogenic methane was generated in large quantities. The cores recovered from Site 154 were very disrupted. Tremendously large gas expansion pockets were recorded in core descriptions and core photographs (Edgar et al., 1973). The drilling was abandoned at a relatively shallow depth of 272 m because of the increasingly abundant gas emanations. The gas recovered from cores of Site 154 was analyzed by Claypool et al. (1973) and determined to be of biogenic origin. Table 4 shows that all gas samples from Site 154 were composed almost exclusively of methane ($CH_4/C_2H_6 \geq 2,500$) with a mean ^{13}C enrichment of -73.4 per mil. Both of these values are typical of biogenic gas.

It is possible that gas hydrates were drilled at Site 154. Abundant gas being released from the cores violently enough that the bedding structures were totally disrupted is suggestive of the degassing behavior observed in documented instances of hydrate recovery. There is no mention of the long shipboard core degassing periods, or core liner extrusion thought to be specific to gas hydrate dissociation; thus, the gas pockets in Site 154 cores may be from simple pore water exsolution of gas. However, it is notable that the site was drilled in January 1971, before much published information was available on the properties of gas hydrated sediments. The depth and temperature conditions at DSDP Site 154 are such that hydrates should be stable, given that sufficient methane was present for hydrate formation. The core descriptions strongly suggest that sufficient quantities of methane were available for gas hydrate formation in the sediments of the Colombia Basin in the area of DSDP Site 154.

Although confirmed recoveries of gas hydrates would make assessment of the gas hydrate resource potential of the Colombia Basin study region more confident, the lack of such should not be interpreted as strong evidence against hydrate presence. The sediments which would be the most propitious for hydrate-forming gas generation are the basinal and marginal turbidites. These sediments are largely unsampled. A number of shallow piston cores of basinal sediments have been taken by LDGO. However, in the only documented probable occurrence of gas hydrates in deep basinal turbidites in the Sigsbee Abyssal Plain of the Gulf of Mexico, detectable hydrate presence was not noted above a subbottom depth about 100 m (Krason et al., 1986). Deep drilling of the basinal and marginal sediments is thus indicated for confirmation of hydrate presence. Conventional piston cores only penetrate to depths where escape of gas by diffusion to the sea floor may lead to dissociation of shallow gas hydrates.

TABLE 4.

RESULTS FROM ANALYSIS OF GAS FROM DSDP SITE 154.
After Claypool et al., 1973.

Depth below sea floor, m	Component (Volume %)			$\delta^{13}C$, ‰
	CH_4	C_2H_6	CO_2	CH_4
60	99.6	<0.005	0.40	-81.3
110	99.8	0.01	0.23	-74.8
190	99.9	0.04	0.10	-69.1
225	99.4	0.03	0.52	-71.9
235	99.8	0.01	0.19	-69.7

Geochemistry

Organic Matter Content

Data on the organic matter content of sediments of the Colombia Basin Study Region are limited to analyses of DSDP cores. A number of shallow piston cores collected by LDGO were analyzed for organic carbon content in conjunction with the U.S. National Oceanographic and Atmospheric Administration's CLIMAP project. However, the only surviving records of the analyses which were made available to us were computer printouts composed of meaningless values. No one connected with the original project could decipher the data. Although the DSDP cores are not representative of the study region as a whole, they do suggest general trends. The organic carbon content of each DSDP site on Leg 15 has been graphically illustrated on the lithological column presented in the Basin Analysis part of this report (Figures 5, 7, 9, and 12).

Site 151 was located on the west flank of the Beata Ridge. The upper 365 m of the sediment section was composed of chalk and marl ooze (Figure 5). The TOC value of this pelagic interval averaged less than 0.1% (Bode, 1973). A 14 m section beneath an unconformity was coarser grained and of terrigenous origin. This sediment, presumably deposited prior to uplift of the Beata Ridge, was found to be very organic-rich with a mean TOC value of 3.4% (Bode, 1973).

Site 152 was cored to a depth of 478 m on the lower flank of the Nicaragua Rise at 100 m above the level of the nearby Colombia Basin abyssal plain. The section was composed entirely of pelagic carbonates resting directly on igneous basement (Figure 7). Most samples tested for organic carbon had TOC levels below the limit of determination of the LECO method (Bode, 1973). The approximate mean TOC value for Site 152 was 0.02% (Bode, 1973).

Site 153 was located north of the Aruba Gap on the south flank of the Beata Ridge. Over 700 m of organic-lean pelagic sediment, averaging less than 0.2% TOC, was drilled. Beneath these carbonate deposits, hemipelagites and turbidites with highly variable organic carbon values averaging 1.1% TOC were recovered. These organic-rich sediments ranging up to 6.2% TOC were deposited prior to uplift.

Site 154 was located in the southwestern Colombia Basin on a small ridge which was uplifted relatively recently. The upper 150 m of sediment was gassy pelagic carbonate ooze with a mean TOC value of 0.16%. An underlying volcanic-terrigenous sequence which was deposited in the early Pliocene prior to the uplift of the ridge was organic-rich and very gassy. This deeper section of more typical basin floor sediments averaged 0.8% TOC, but some layers within the terrigenous sediments had TOC values of as much as 5.9%.

Site 502 was drilled near Site 154 on a much larger uplift, the Mono Rise. Pelagic carbonates were cored to a depth of 227 m. Sediments deposited prior to the uplift of Mono rise were not penetrated. The pelagic sediments averaged 0.4% TOC (Figure 42; Gardner, 1982).

A common pattern of organic carbon distribution emerges in the DSDP cores from the Colombia Basin. The pelagic carbonate muds which were deposited on these elevated locations are very lean in organic carbon. With the possible exception of Site 502, the pelagic carbonates do not appear to have sufficient organic carbon to sustain bacterial methanogenesis. However, in all sites where basin floor sediments deposited prior to uplift were penetrated (151, 153, 154) organic-rich turbidites and hemipelagites with presumably greater gas generative potential were encountered. These carbonaceous pre-uplift sediments range in age from Turonian to Pliocene. Thus, it appears that organic-rich terrestrial sediments were being deposited in the Colombia Basin or its precursors over a long period of time. Organic productivity and preservation, climate, and terrestrial input have all varied considerably since the early Pliocene, and thus the unsampled terrigenous sediments of Pliocene to Holocene age from the Colombia Basin undoubtedly differ from the Turonian to Pliocene terrigenous sediments analyzed by the DSDP. However, the Cenozoic turbidites and hemipelagites which constitute the vast majority of the Colombia Basin sediments within the gas hydrate stability zone may be similar to the drilled terrigenous sediments in organic carbon content and gas generative potential.

Prell (1978) cited evidence that indicates that Quaternary sediments from the Rio Magdalena are organic-rich. A region of very high marine organic productivity was found to coincide with an upwelling zone over the Magdalena Fan. Prell (1978) stated that the combination of this abundant marine organic carbon production and the influx of terrestrial organic material produces a sedimentary signature in the form of a greatly enhanced carbonate dissolution zone which diminishes away from the Magdalena Fan. Since most of the basinal sediments of the Colombia Basin appear to be derived from the Magdalena Fan, the probability of finding organic-rich Quaternary turbidites and hemipelagites in the Colombia Basin should be considerable.

Organic Matter Type

Since the sediments best suited to be gas hydrate source host rocks are generally unsampled, little is known about their kerogen character. No published studies have typed the organic matter of the sediments of the study region. Based on the tremendous volume of sediment which has been deposited by the Rio Magdalena, it is probable that terrestrial organic matter (Type III of Tissot and Welte, 1978) is the dominant type. However, the previously mentioned evidence for an upwelling zone over the Magdalena Fan cited by Prell (1978) suggests that some Quaternary sediments may contain some marine organic matter (Types I and II of Tissot and Welte, 1978).

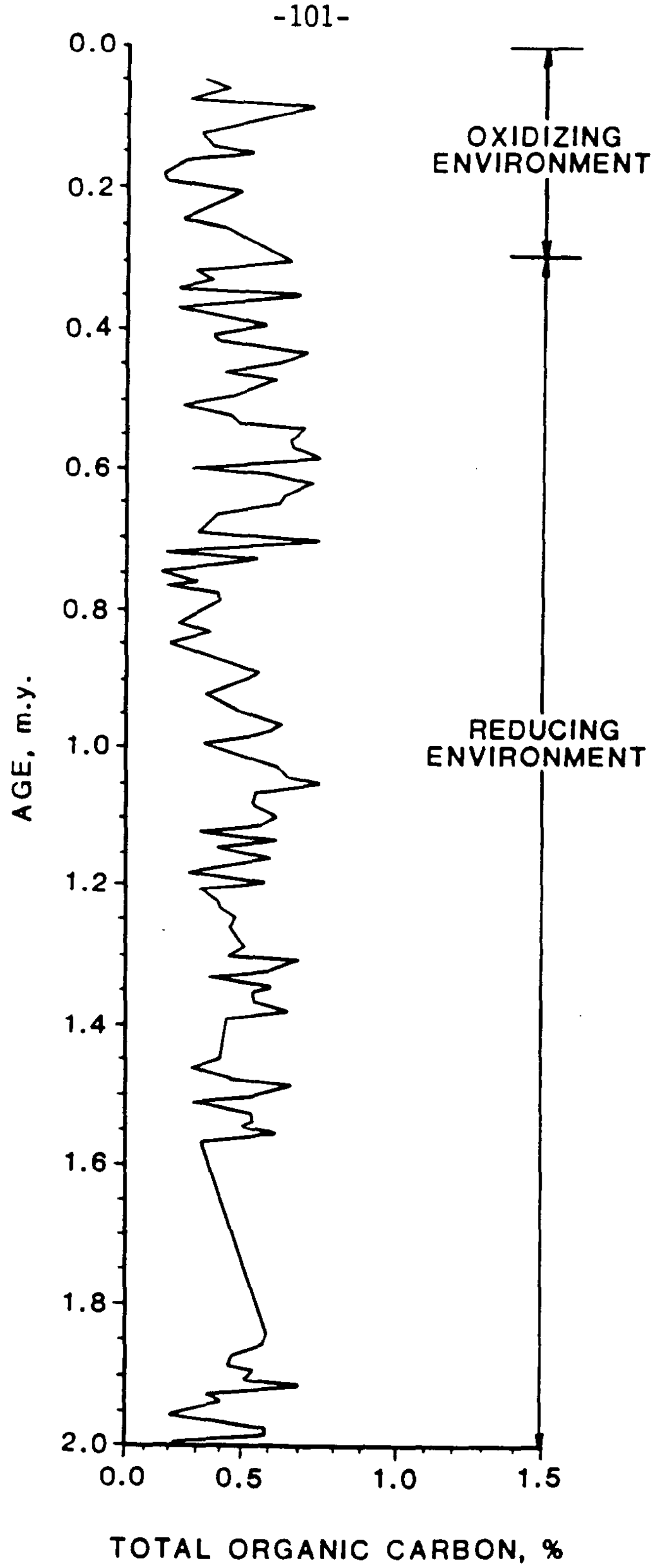


Figure 42. ORGANIC CARBON CONTENT OF DSDP SITE 502

After Gardner, 1981

Organic Matter Preservation

There is no evidence of anoxic ocean bottom environments in the study region. Published hydrographic data indicates that the sea water is well oxygenated at depth (Figure 43). Mean oxygen concentration values of 4.8 mL/L are recorded at depths greater than 1,500 m (Helminski, 1975). There is little variance in this or shallower values indicating that no anoxic zones were surveyed. The upwelling described by Prell (1978) should agitate the bottom waters to the extent that the stratification necessary for establishing local zones on disoxic conditions could not be established or maintained. The generally accepted worldwide Cretaceous anoxic event would not be expected to have had as much effect on the proto-Colombia Basin, a deep oceanic realm, as in the epeiric basins for which most evidence of anoxia exists. In most instances the sedimentation is sufficiently rapid in the Colombia Basin that Cretaceous sediments are deeper than the zone of hydrate stability. However, these potentially rich Cretaceous source rocks could be important for generating biogenic gas which could migrate short distances vertically to the hydrate stability zone. Upon deep burial, any Cretaceous rocks resulting from such an anoxic event may contribute thermogenic gas to hydrates.

Sediment accumulation in the Colombia Basin is rapid. The predominantly pelagic sediment sampled by DSDP Leg 15 was quickly deposited; typical rates range from 1 to 5 cm/1,000 yr (Figure 44). DSDP Site 502 had a very consistent Miocene to Holocene sedimentation rate of 2.9 cm/1,000 yr. As previously stated, these pelagic carbonate sediments have very low gas generative potential. The turbidites and hemipelagites covering the majority of the study area were not drilled by DSDP. Determination of rate of sedimentation of turbidite sequences is difficult because of the episodic nature of turbidity currents, the relationship of their sedimentation rate with eustatic sea level fluctuation, and the mixing of datable organisms during sedimentation. Prell (1978) showed that the rain of pelagic carbonate ooze was relatively constant through time during the Quaternary. From this observation he inferred that the non-carbonate content of the sediment is proportional to sedimentation rate. Thus, the turbidite-dominated basin floor and continental slope with abundant terrestrial detritus represents a regime of significantly higher sedimentation rate than the DSDP sampled pelagic domain. One may therefore conclude that those terrigenous areas, which are more favorable for hydrate development based on probable organic matter content, received sedimentation at a rate greater than 3 cm/1,000 yr. Such rapid sedimentation should be favorable for organic matter preservation.

One observation directly addressing the depth of the sulfate reducing zone, which could provide evidence on the preservation of organic matter in the Colombia Basin was found. DSDP Site 502 showed a color change at 7 m subbottom from browns and reds to grays and greens (Gardner et al., 1982). The scientific party established this as the boundary between oxidizing and reducing conditions. The 7 m depth corresponds to 290,000 yr at 2.4 cm/1,000 yr accumulation rate. Organic material would have been subjected to aerobic oxidation processes for such a period before the organic material remaining would be available for bacterial methanogenesis. No distinct trend toward diminishing TOC values for the 50,000 to 290,000 year section from Site 502 is noted in Figure 42. It may thus be inferred that (1) the major depletion of organic matter occurred quickly and is not reflected in the figure, (2) sampling density was insufficient to detect the effects of aerobic

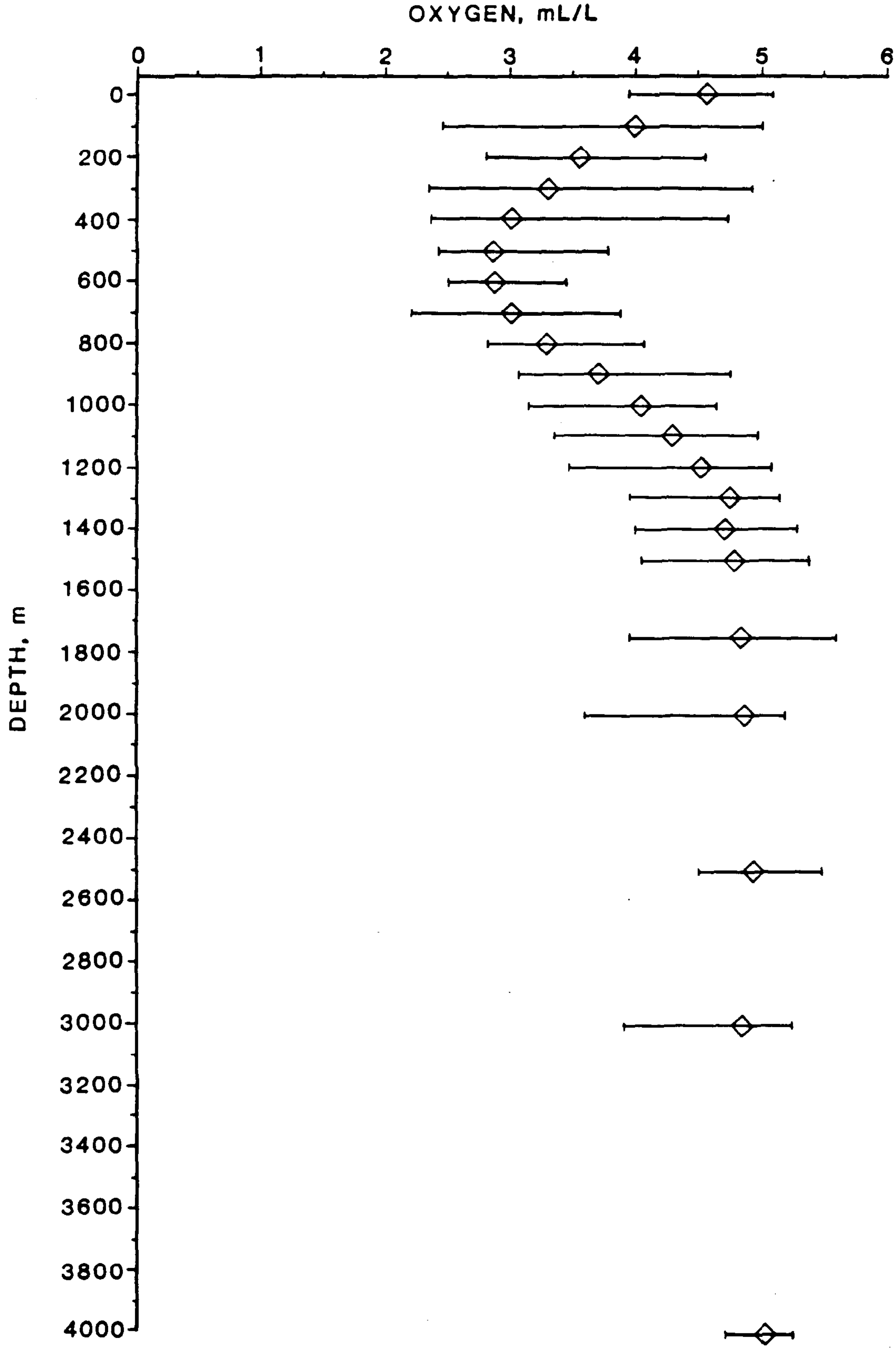


Figure 43. MEAN OCEAN WATER OXYGEN CONTENT OF THE COLOMBIA BASIN

After Helminski, 1975

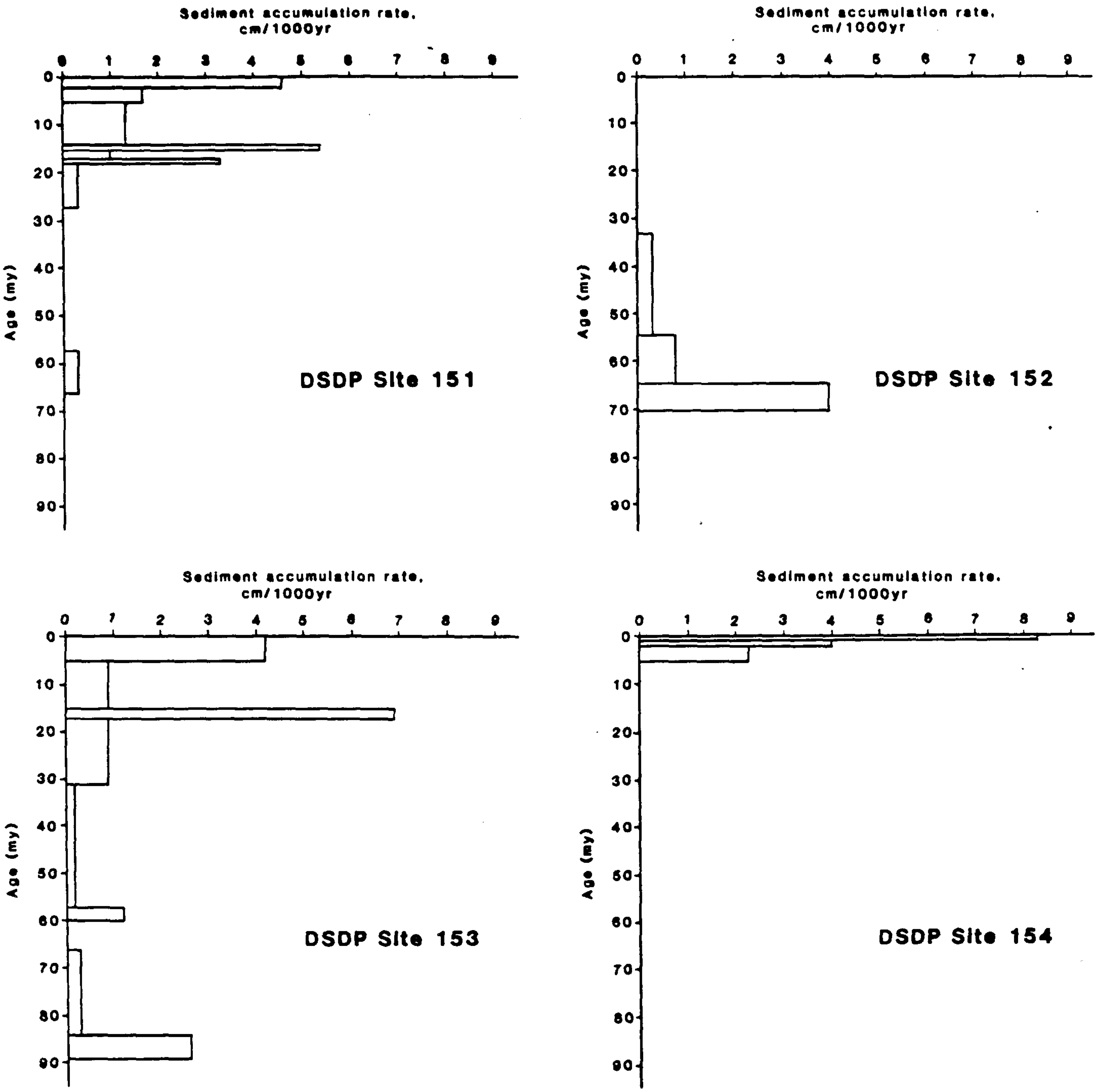


Figure 44. SEDIMENTATION RATES IN THE COLOMBIA BASIN FROM DSDP LEG 15

After Edgar et al., 1973

oxidation, (3) variation of organic carbon content between layers overwhelms the expected sequential decrease in TOC with depth to the top of the sulfate reduction zone, (4) the organic matter was relatively refractory to oxidative decomposition, or (5) a combination of these factors is responsible.

In summary, from the limited information available it seems that rapid sedimentation in the Colombia Basin should lead to good organic matter preservation. Direct sampling of potential gas hydrate host sediments, basin floor and continental slope turbidites, would permit clarification of this conclusion which was extrapolated from the pelagic domain.

Pore Water Chemistry

Data on pore water chemistry of the Colombia Basin study region is sadly lacking. No data exist for the four holes drilled in the region during DSDP Leg 15. The investigators were concerned that pore water analyses from earlier legs were suspect (Broecker, 1973). Sampling procedures used in these early cruises permitted contamination of the pore water samples with the sea water used as a drilling fluid. Leg 15 made use of more reliable and time consuming pore water analysis procedures. These procedures were applied to only three sites in Leg 15, none of which were in the Colombia Basin study region. The Colombia Basin DSDP sites were unfortunately overlooked in the transition to more modern analytical procedures; neither the suspect methods, nor the more modern methods were used to analyze the pore water from Colombia Basin cores.

The only reported chemical measurement from DSDP Site 502 of Leg 68 was for salinity (Gardner et al., 1982). The salinity increased from 3.55% at 2 m subbottom to 3.96% at 14.5 m. The salinity then decreased to 3.74% before rising to 3.82% at 30 m. The pore water salinity at Site 502 remained fairly constant from 37 m to 143 m, ranging between 3.45% and 3.66%. One salinity spike occurred at 135 m with a value of 3.96%.

Water Temperature

The water temperature of the Caribbean and other hydrographic data have been summarized by Helminski (1975). Water temperature data for the Colombia Basin study region averaged over all 12 months is summarized in Figure 45. Water temperature asymptotically approaches 4° C with depth. The wide fluctuation of temperature values in the upper 400 m represents seasonal warming and cooling. Below 400 m the temperature range probably represents true differences in water temperature among sampling sites due to factors other than seasonal fluctuation.

Sediment Temperature

Epp et al. (1970) compiled data on heat flow in the Caribbean. The results from shallow temperature probes from various LDGO cruises were

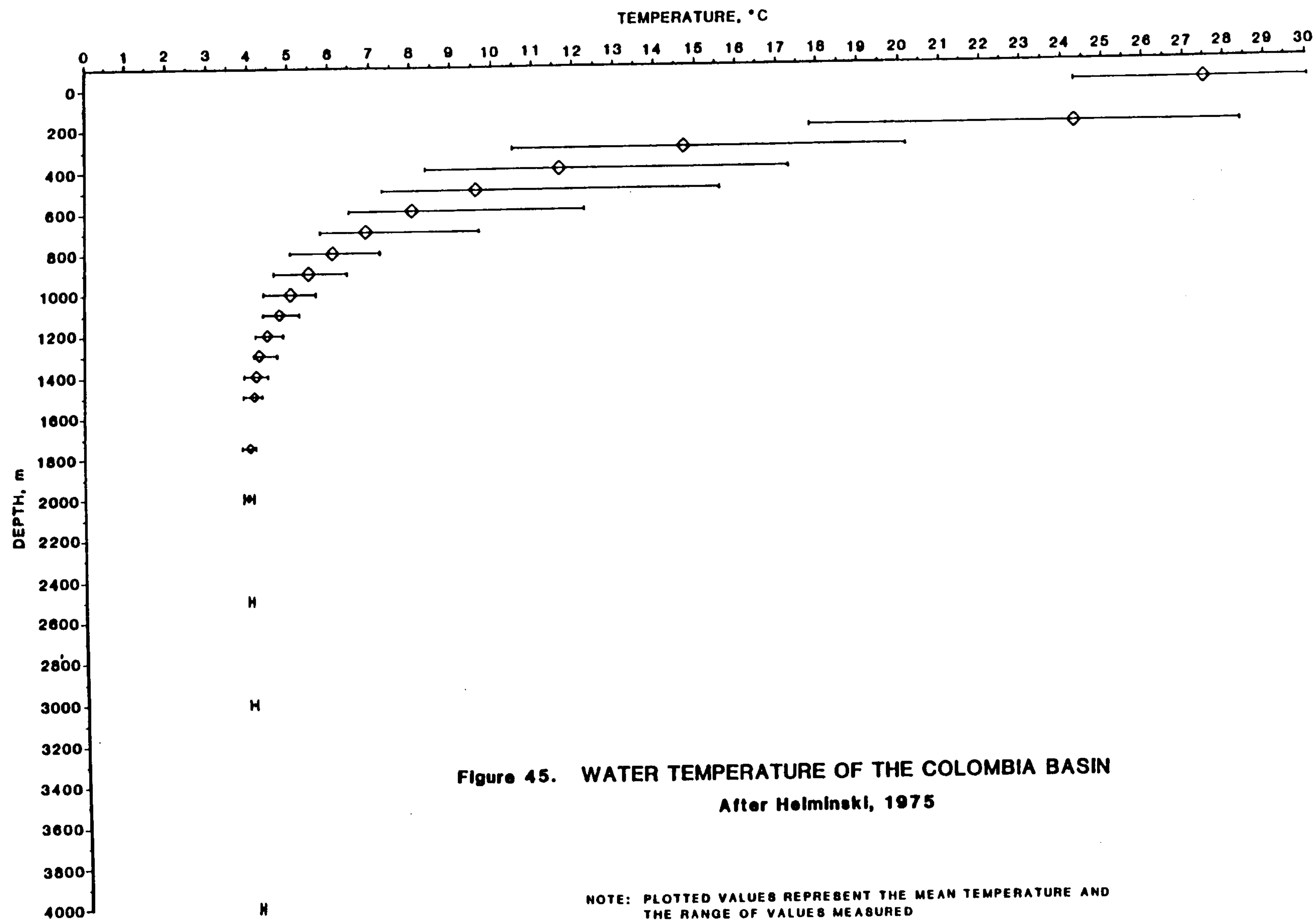


Figure 45. WATER TEMPERATURE OF THE COLOMBIA BASIN
After Helminski, 1975

NOTE: PLOTTED VALUES REPRESENT THE MEAN TEMPERATURE AND THE RANGE OF VALUES MEASURED tabulated. Epp et. al. (1970) also measured the thermal conductivity of the shallow sediments at the temperature analysis sites and thus were able to calculate geothermal gradients from the heat flow values. Heat flow and geothermal gradient values for 23 sites in the Colombia Basin study region are mapped in Figure 46. The mean regional geothermal gradient is 5.8° C/100 m. The scatter about the mean is large; the gradient varies from 2.4 to 11.6° C/100 m between two locations on the Nicaragua Rise 180 km apart. The standard deviation of the measured geothermal gradients is 1.8. There are no geothermal gradient measurements on the deformed belts near where BSRs are located. The sparse measurements on the abyssal plain adjacent to the deformed belts show low values (3.5 to 5.0° C/100 m) over the lower Magdalena Fan and high values (5.8 to 7.3° C/100 m) at sites distant from the fan.

Geothermal gradients calculated by Epp et al. (1970) can be compared with geothermal gradients derived from BSR depth. The geothermal gradient measurement closest to a seismic line with a BSR is station ZEP-4 which is 10 km from seismic line 132 (Figure 26). Station ZEP-4 shows a geothermal gradient of 6.0° C/100 m. Using a probable ocean floor temperature of 4.2° for 3,500 m water depth, the expected subbottom depth to the base of hydrates would be 332 m for biogenic hydrates and 379 m for thermogenic hydrates using the dissociation data of Holder and John as listed in Kuuskraa et al. (1983). At a seismic velocity of 2,000 km/sec in sediment, a subbottom depth of 0.33 to 0.37 sec would be expected of a BSR. The BSR in line 132 averages 0.65 sec subbottom depth which would be expected with a geothermal gradient of 3.3° C/100 m.

Station V24-21 from the study by Epp et al. (1970) shows a geothermal gradient of 7.3° C/100 m at a location 60 km from line CT1-21. At 3,000 m water depth and with a bottom water temperature of 4.12°, a geothermal gradient of 7.3° C/100 m would yield a base of hydrate stability at 254 m for biogenic and 299 m for thermogenic hydrates. At 2,000 m/sec seismic velocity, the BSR would be expected at 0.25 to 0.30 sec subbottom. BSRs at a water depth of 3,000 m along nearby line CT1-21 (Figure 32) occur at 0.45 to 0.50 sec. These BSR depths correspond to a much lower geothermal gradient of 3.5 to 4.5° C/100 m for the lower reaches of line CT1-21.

A similar discrepancy between BSR derived gradients and those calculated by Epp et al. (1970) is observed with line CT1-25 and station V24-20. A probable maximum subbottom depth of hydrate stability of 323 to 378 m is calculated for the 5.8° C/100m gradient found at V24-20 which would correspond to a BSR at 0.32 to 0.38 sec. The BSR on line CT1-25 is found at 0.60 to 0.68 sec subbottom at 3,000 m water depth. Such a BSR depth corresponds to a geothermal gradient of approximately 3.5° C/100 m.

At each location where a BSR is tested against the thermal gradient measured by Epp et al. (1970), the BSR derived value is 40% less than that from direct probe measurement. The discrepancy may be due to factors determining BSR depth. A BSR deeper than expected from a given geothermal gradient could result from a pressure gradient greater than hydrostatic, cool bottom water temperatures, or a very stable gas mixture. Von Huene and Lee (1983) documented abnormally high pore pressures in accretionary complexes of subduction zones. Overpressuring, which would tend to deepen a BSR, is obviously present to some extent along the marginal deformed belt offshore of Colombia as witnessed by the abundance of mud diapirs. An overly warm bottom water temperature could not cause such a large

FIGURE 46, Heat Flow and Geothermal Gradients of the Colombia Basin Study Region, is located in the pocket at the end of the report.

discrepancy in expected versus recorded BSR depths at a given geothermal gradient. Among 47 observations at 3,000 m in the Colombia Basin the range of water temperature values was only 0.20° C (Helminski, 1975). A water temperature as much as 1° C lower than the reported 4.12° mean would increase the hydrate zone by only 15 m, clearly insufficient to account for the observed disparity. An abundance of H_2S, CO_2, or higher hydrocarbons could stabilize hydrates and thus produce a deeper than expected BSR. The necessary stability increase for a 40% difference in expected and observed BSR depth would require a gas mixture much depleted in methane, unlike any yet reported from deep sea sediments.

The model used to calculate the depth of hydrate stability may be at fault. However the model is based on hard laboratory data, and the results generally agree with similar models. The model used herein generally estimates hydrates to be stable at greater depths than some simpler approaches because of the use of a more sophisticated algorithm based on successive approximations.

The difference noted between BSR derived geothermal gradients and gradients obtained by Epp et al. (1970) may have been caused by a combination of any of the above factors. A BSR which is too shallow for an expected gradient could easily be explained as a prominent hydrate layer within the hydrate stability zone. No simple explanation is apparent for a BSR which is deeper than expected.

The possibility remains that the geothermal gradients calculated by Epp et al. (1970) do not adequately represent the geothermal gradients in the BSR depth range (400 - 700 m). The estimates were based on measured heat flow and thermal conductivity of sediments near the sea floor. Assuming that the heat flows measured by Epp et al. (1970) are accurate, nonrepresentative values of sediment, thermal conductivity may have resulted in overly high derived geothermal gradients. Thermal conductivity of a sediment varies depending on the thermal conductivity of the constituent framework grains and interstitial water. Water has a low thermal conductivity, 0.052 cal/m hr K (Weast, 1976). Dry consolidated rocks have thermal conductivities on the order of 1.5 to 5 cal/m hr K (Weast, 1976). The thermal conductivity of an unconsolidated sediment would thus largely depend on the water content of the sediment. Highly porous sediment near the sea floor is 60 to 70% water and has a substantially lower thermal conductivity than a deeper, less porous sediment. Thermal conductivity and geothermal gradient are inversely related. For a given heat flow a layer of loose, porous sediment near the sea floor having a low thermal conductivity should have a higher geothermal gradient than a deeper compacted sediment with correspondingly higher thermal conductivity. The depth of the sediment samples used by Epp et al. (1970) was not reported, but it is safe to assume that the sediment was from within the penetration capability of a piston coring device, up to 10 m. At 10 m subbottom, the sediments used for thermal conductivity would contain much water and have lower thermal conductivities than those of the entire sediment pile. Thus we can infer that the geothermal gradients of 2.4 to 11.2° C/100 m averaging 5.8° C/100 m reflect only the gradient of the uppermost sediment layers. The geothermal gradient of the sediments at a depth where gas hydrate development is expected is more closely approximated by solving BSR depth equations for geothermal gradient which yields 3.5 - 4.0° C/100 m for the Colombia Basin continental margins.

Vertical Distribution of Gas Hydrates

Use of water bottom temperature data and inferred geothermal gradients permits the calculation of the theoretical lower limit of hydrate stability for various water depths in the Caribbean. For these estimates the experimental gas hydrate dissociation pressures and temperatures obtained by John and Holder as summarized in the DOE gas hydrates handbook (Kuuskraa et al., 1983) were used. The methane-water system data were selected for determination of stability parameters for biogenic hydrates. The data from a mixture of methane (90.6%), ethane (6.6%), propane (1.8%), iso-butane (p.5%), and normal butane (0.5%) were chosen to model the dissociation of a thermogenic gas. The pressure and temperature data were transposed to the form of ln(P) and (1/T). Least squares fitting of a regression line of a plot of ln(P) vs. l/T generated empirical coefficients a and b to be used in the standard form of $\ln(P) = a + b(1/T)$. A simple computer program was used to evaluate the physical possibility of hydrate existence based on the empirical equation for each 1 m interval of sediment under specified conditions of water depth and temperature, and geothermal gradients. The results were checked against other standard curves for accuracy.

Minimum Water Depth

If a realistic geothermal gradient assumption of 4° C/100 m is used, the water depth and temperature data from Helminski (1975) can be used to assign reasonable minimum water depths for hydrate preservation. Possible scenarios which were modeled include the minimum, mean, and maximum water temperatures reported by Helminski (1975) for 100 m depth intervals. The results of the simulation are shown in Table 5.

If the maximum temperature recorded for each depth interval is considered, thermogenic gas hydrates are not stable beneath water shallower than 500 - 600 m. Methane hydrate is substantially less stable under these conditions; it can exist only beneath waters deeper than 700 - 800 m.

Using the mean annual temperature values for the Colombia Basin, thermogenic gas hydrates are stable beneath 300 - 400 m and deeper beneath sea level. The shallowest appearance of biogenic gas hydrates would be at a minimum depth of 500 to 600 m, closer to 600.

The results of the analysis assuming the minimum temperature reported for each depth to be the hydrate controlling temperature gives unrealistically shallow minimum water depths of 200 - 300 m for thermogenic hydrates and 500 - 600 for biogenic hydrates.

Thermogenic Hydrocarbon Generation

Deep penetration multichannel seismic lines of the Colombia Basin show that the sediment pile becomes thicker near the deformed belts. No comprehensive total sediment isopach map of the region is available. Estimates

TABLE 5.

CALCULATED THICKNESS OF GAS HYDRATE STABILITY ZONE IN THE COLOMBIA BASIN

Water depth, m	Thickness of Gas Hydrate Stability Zone, m			Gas type
	Maximum annual water temperature	Mean annual water temperature	Minimum annual water temperature	
300	0	0	0	Biogenic
	0	0	69	Thermogenic
400	0	0	0	Biogenic
	0	66	186	Thermogenic
500	0	0	0	Biogenic
	0	170	247	Thermogenic
600	0	14	71	Biogenic
	110	242	289	Thermogenic
700	0	94	131	Biogenic
	212	294	327	Thermogenic
800	115	152	183	Biogenic
	302	335	362	Thermogenic
900	165	196	229	Biogenic
	337	366	389	Thermogenic
1,000	212	231	250	Biogenic
	273	390	408	Thermogenic
1,100	243	260	268	Biogenic
	395	441	419	Thermogenic
1,200	271	284	293	Biogenic
	416	428	436	Thermogenic
1,300	294	303	309	Biogenic
	432	441	446	Thermogenic

TABLE 5. (continued)

CALCULATED THICKNESS OF GAS HYDRATE STABILITY ZONE
IN THE COLOMBIA BASIN

Water depth, m	Thickness of Gas Hydrate Stability Zone, m			Gas type
	Maximum annual water temperature	Mean annual water temperature	Minimum annual water temperature	
1,400	-	321	-	Biogenic
	-	453	-	Thermogenic
1,500	-	337	-	Biogenic
	-	464	-	Thermogenic
1,750	-	370	-	Biogenic
	-	486	-	Thermogenic
2,000	-	398	-	Biogenic
	-	504	-	Thermogenic
2,500	-	442	-	Biogenic
	-	553	-	Thermogenic
3,000	-	478	-	Biogenic
	-	556	-	Thermogenic
4,000	-	534	-	Biogenic
	-	593	-	Thermogenic

based on the limited seismic coverage of the study region shows that the sediment pile on the abyssal plain adjacent to the deformed belts range in thickness from 2 sec (2,500 m) to 7 sec (8,400 m). Beneath the accretionary wedges of the marginal deformed belts, 3 sec (4,500 m) to 8 sec (10,500 m) of deformed sediments seems likely. These great depths of sediments indicate that some of the Cretaceous and early Tertiary sediments for the Colombia Basin should be thermally mature with respect to oil and natural gas generation. The thermogenic hydrocarbons may migrate along structural pathways to shallow depths and thus augment biogenic methane in the formation of gas hydrates.

Thickness of Sediment

Each seismic line discussed earlier in regards to BSR configuration can be examined to determine depth to igneous basement.

Line CT1-21 (Figure 32). As interpreted by Lu and McMillen (1983), the oceanic basement dips landward reaching a depth of 7 sec just landward of the marginal deformed belt which corresponds to a sediment thickness of 2.6 sec. The exact thickness to which 2.6 sec travel time corresponds may vary depending on the seismic velocity assigned to the deeper units. Lu and McMillen (1983) present different seismic velocity figures for the sediment stack; 2.6 km/sec seems to be a reasonable middle ground. At this velocity, the 2.7 sec thickness of sediment corresponds to 3,500 m of sediment. Beneath the accretionary wedge the basement reflectors dip off of the section. By projecting the crust landward, a sediment thickness of 4 to 6 sec (5,000 - 7,500 m) is obtained for the accretionary wedge. It is possible that the accretionary wedge overlies sections of stranded oceanic crust at depths much less than those obtained from simply projecting the crust down at the apparent subduction angle (Seely, 1979). Thus the sedimentary section may also be thinner, but a minimum thickness of 4 sec (5,000 m) of sediments under the accretionary wedge is estimated.

Line PN1 (Figure 36). At least 2.5 sec (3,200 m) of sediment is seen above the basement on the abyssal plain. The thickness under the accretionary prism ranges from 3 - 6 sec (4,000 - 8,000 m).

Line CT1-25 (Figure 33) has been interpreted by Lu and McMillen (1983) to represent sediments down to the deepest reflectors illustrated, 8 sec. This yields an abyssal plain sediment depth of 4 sec (5,000 m) as a minimum. Details are obscured beneath the deformed belt, but it is likely that up to 6 sec (8,000 m) of sediments exist there.

Line 127 (Figure 23) crosses the Magdalena Fan. The basement has a subbottom depth of 3 sec (4,000 m) in the lower fan and up to 7 sec (9,000 m) near the Colombian coast.

Line 129 (Figure 24) displays prominent multiples which obscure the basement reflectors. At least 5 sec (6,500 m) of sediments are seen above the multiple on the abyssal plain. At least 7 sec (9,000 m) of sediments is projected beneath the deformed margin.

Line 130 (Figure 25) was interpreted by Ladd and Truchan (1983) to show 7 sec (9,000 m) of sediments beneath the abyssal plain to 8 sec (10,500 m) beneath the accretionary prism. Ladd and Truchan (1983) describe a slice of stranded igneous crust beneath the Rancheria Basin giving a total sediment thickness of 4 sec (5,000 m) beneath this forearc basin.

Line 132 (Figure 26) does not extend to the abyssal plain. Beneath the accretionary wedge 4 to 6 sec (5,000 to 8,000 m) of sediments occur above the basement reflectors.

Lines B-3 and 1422 (Figures 38 and 37) show that the sediment pile is thinner beneath the Aruba Gap than farther southwest. A section 2.5 sec (3,200 m) underlies the abyssal plain. The accretionary wedge is composed of over 4 sec (5,000 m) of sediments.

Rate of Sedimentation

The sedimentation rates calculated from DSDP sites in the Colombia Basin study region are variable. An estimated mean of 2.5 cm/1,000 yr was assumed for the region in a previous section of this report.

The sedimentation rates at areas of the region which are covered with thick turbidite sequences are necessary parameters for calculating possible thermal maturity. A rough estimate of the relevant sedimentation rate can be derived by dividing the sediment thickness observed on high quality seismic sections by the estimated age of the sediment stack. The age of the Colombia Basin sediments is not well known. Horizons immediately above igneous basement have been dated as old as Turonian by DSDP scientists. We have assumed that the lowermost sediments of the section are 100 m.y. old. Sedimentation rates from DSDP holes penetrating the sedimentary sequence show no distinct trend toward higher or lower sedimentation rate during any one epoch (Figure 44); we have assumed a constant rate of sedimentation through time corresponding to the mean sedimentation rate for the 100 m.y. period.

Offshore of Panama an undisturbed sedimentary sequence 3,200 - 3,500 m was derived. This yields a probable sedimentation rate of 3.2 to 3.5 cm/1,000 yr.

The 5,000 m thickness of the abyssal plain sediments offshore of northwest Colombia results in a 5.0 cm/1,000 yr sedimentation rate.

Under the Magdalena Fan, rapid sedimentation has produced a section 4,000 to 9,000 m thick. The sedimentation rate derived from these figures 4 to 9 cm/1,000 yr with an arbitrarily selected representative rate of 7 cm/ 1,000 yr.

The deformed margin northeast of the Magdalena Fan shows deep sediment accumulations. It is estimated that 6,500 to 8,000 m of sediment overlies the undeformed abyssal plain offshore of the Sierra de Santa Marta. Very rapid sedimentation of 6.5 to 8 cm/1,000 yr is thus indicated. An intermediate rate of 7 cm/1,000 m is selected for modeling.

Sedimentation beneath the Aruba Gap has been slow. The 3,200 m sediment stack was deposited at an average rate of 3.2 cm/1,000 yr.

Burial History Reconstruction

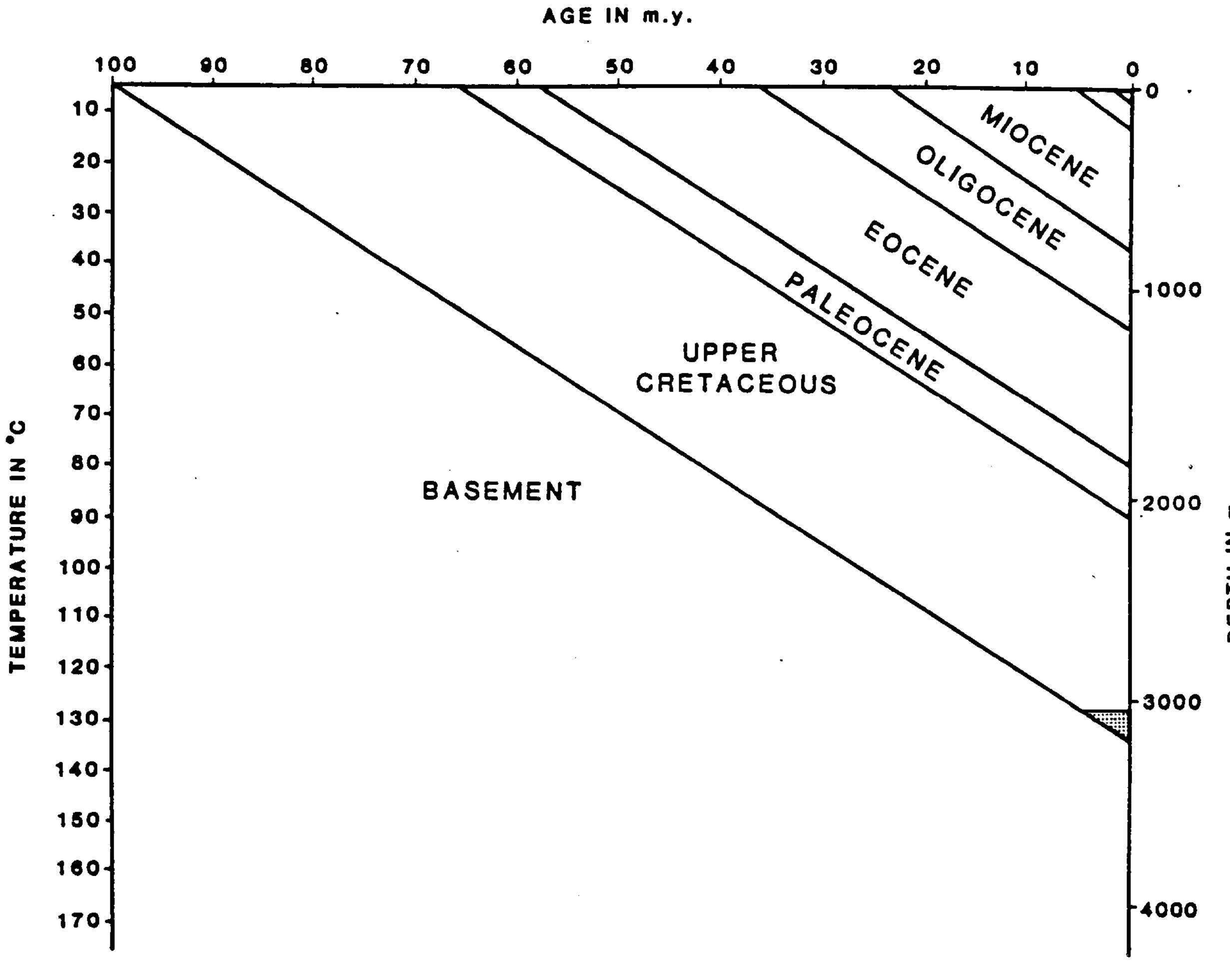
Derived geothermal gradients and estimated sedimentation rates were used to make simple Lopatin burial history reconstructions to assess the thermal maturity of the deep abyssal plain sediments adjacent to the continental margins. The use of a constant sediment accumulation rate is admittedly simplistic. The sedimentation rate should be greater in the more recent strata since voluminous proximal turbidites from the continental margin increase in frequency and thickness as the oceanic plate nears the trench. However, there is no drilling in the turbidites of the basin floor to give us a clearer quantitative picture of temporal variation of sedimentation. It is assumed that the conservative estimates of sediment thickness and compaction will compensate for the non-linear sedimentation history.

Lopatin burial history reconstructions illustrate sediment accumulation through time, and the resulting thermal maturity of the sediment section. The thermal maturity derived for the section is expressed in units of TTI. According to Waples (1980), TTI can be correlated with other standard maturity measures. The TTI range of 15 - 160 corresponds to a vitrinite reflectance value of 0.65 to 1.30, generally considered to be the principal zone of oil formation. Natural gas can exist deeper than petroleum; wet gas (i.e. a mixture of CH_4 and heavier homologs) can exist to a TTI value of 1,500. Gas composed of thermogenic methane, CO_2, and H_2S can exist to much greater depths than wet gas; the deepest known occurrence of dry gas is equivalent to a TTI value of 65,000.

Disagreement exists as to the level of thermal maturity at which thermogenic generation of gas occurs. The most widely held view is that summarized by Tissot and Welte (1978) that gas generation is a very slow process until approximately one half of the way through the oil generative stage whereupon it increases rapidly. Gas generation via kerogen degradation is augmented by thermal cracking of existing oil and, thus, continues at higher levels of thermal maturity. A different view is expressed by Hedberg (1980) based on the work of the Soviet scientist Sokolov. In this scenario, thermal gas generation begins at lesser levels of thermal maturity and increases smoothly through the principal zone of oil generation. By this latter interpretation, thermogenic gas generation from source rocks should parallel oil generation, but continue to somewhat higher levels of thermal maturity than that at which oil generation diminishes.

Based on the generalized estimates of sedimentation rates on the abyssal plain of the Colombia Basin adjacent to the marginal deformed belts, three representative burial history reconstructions were derived. These different thermal maturity models used sedimentation rates of 3.2, 5, and 7 cm/1,000 yr, thought to be representative of areal sedimentation patterns.

Offshore Panama and Aruba Gap. The reconstruction for the relatively slow deposition offshore of Panama and in the Aruba Gap used a constant sedimentation rate of 3.2 cm/1,000 yr. The Lopatin diagram (Figure 47)



Geothermal gradient - 4°C/100m. Patterned area represents main zone of thermogenic hydrocarbon production (TTI - 15 to 160), according to Waples (1980).

Figure 47. LOPATIN BURIAL HISTORY DIAGRAM FOR ABYSSAL PLAIN SEDIMENTS OFFSHORE PANAMA AND BENEATH ARUBA GAP, ASSUMED SEDIMENTATION RATE IS 3.2cm/1000yr

shows that at the assumed geothermal gradient of 4° C/1,000 m, only the deepest 100 m of sediments would have reached the oil generation window of TTI = 15. By the interpretation of Tissot and Welte (1978), very little thermogenic gas would have been generated by this level of maturity; whereas, Hedberg (1980) would have interpreted that minor gas generation would be in progress. It is likely that the more recent sediments were deposited more rapidly than deeper strata, due to the increased thickness of proximal turbidites closer to the convergent margin. If this is so, the thermal maturity of the sediments would be less than in the illustrated case.

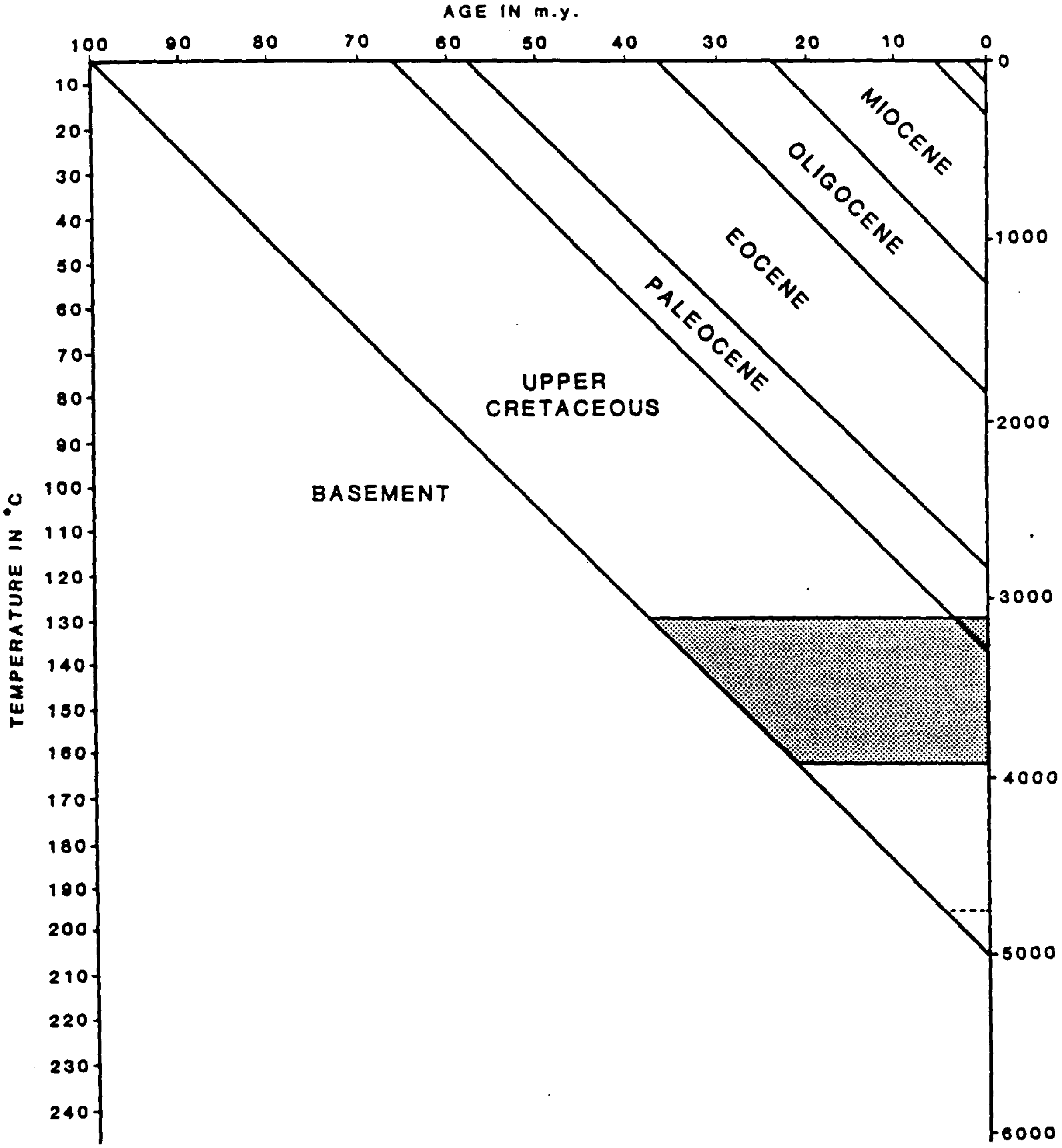
Offshore of Northwestern Colombia southwest of the Magdalena Delta the mean abyssal sediment rate is poorly constrained, but is at least 5 cm/1,000 yr. The burial history diagram (Figure 48) shows that the entire Upper Cretaceous section should be thermally mature. The basal sediments have a TTI value of 3,000, and the Cretaceous-Tertiary boundary shows a TTI value of 23. The depth limit of intense oil generation (TTI = 160) is reached at 1,200 m above the basement. This lower section should be of ideal maturity for gas generation by any proposed interpretation. The upper part of the oil generation window extends into the basal Tertiary rocks. By Hedberg's (1980) interpretation the Paleocene section should be actively generating sizeable amounts of gas.

Magdalena Fan and Offshore of Northeast Colombia. A conservative estimate of the mean sedimentation rate for the Magdalena Fan and the abyssal plain along the northeast trending deformed belt between the fan and the Aruba Gap is 7 cm/1,000 yr. Based on that figure the simplified burial history reconstruction (Figure 49) indicates that over 55% of the sediment pile is mature or overmature for hydrocarbon generation. The principal zone of oil generation occurs at 3,100 - 4,000 m depth in Eocene sediments. The Paleocene and uppermost Cretaceous section is overmature for oil but within the wet gas generation zone. The lower 2,100 m of Cretaceous rocks is in the dry gas zone, where methane is formed largely from thermal cracking of higher molecular weight hydrocarbons. Thus, when 7,000 m of sediment is present, a linear sedimentation rate and a constant geothermal gradient of 4°/100 m would produce a thick section of rocks thermally mature for gas generation.

These simple models are not entirely realistic. Different sedimentation rates, geothermal gradients, and sediment compaction factors would alter the above interpretations. However these models qualitatively illustrate the portions of the abyssal plain sediments which could contribute thermogenic gas to gas hydrates.

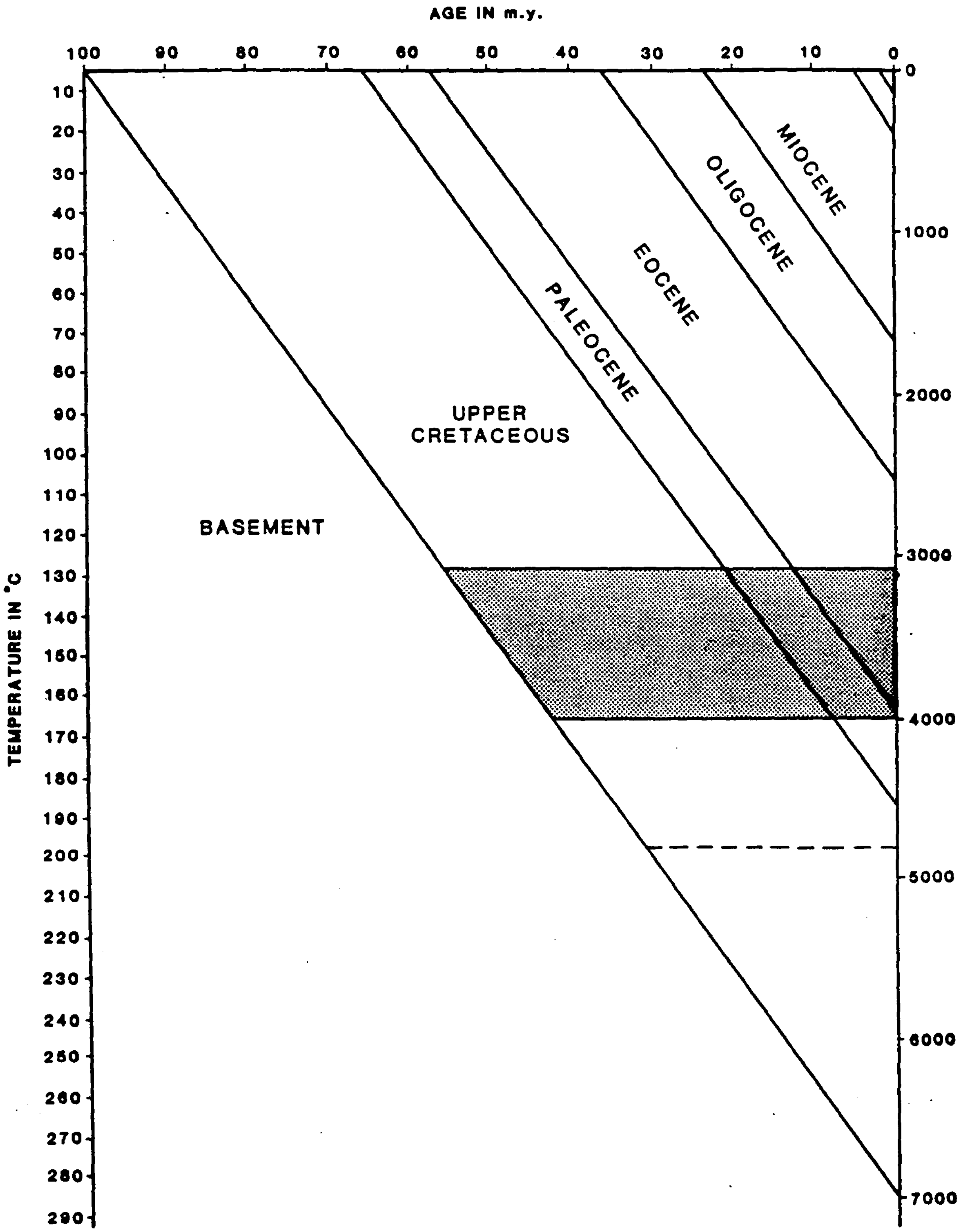
The thermal maturity of the sediments which compose the marginal deformed belts is of much interest. BSRs are abundant in these deformed terranes. The sediments are folded and stacked to yield a thicker section in the deformed belts. Sediments which are thermally immature or marginally mature beneath the abyssal plain could ideally obtain maturity when buried beneath imbricate thrust plates in the accretionary complex. The thermal maturity of sediments in the deformed belts is important also because structural migration pathways abound in the margin settings.

A lack of data on the timing of convergence limits straightforward thermal modeling of the thermal history of the continental margin rocks.



Geothermal gradient - 4°C/100m. Patterned area represents main zone of thermogenic hydrocarbon production (TTI - 15 to 160); dashed line indicates deepest occurrence of "wet" gas (TTI - 1500) according to Waples (1980).

Figure 48. LOPATIN BURIAL HISTORY RECONSTRUCTION FOR THE ABYSSAL PLAIN OF NORTHWESTERN COLOMBIA, ASSUMED SEDIMENTATION RATE IS 5cm/1,000yr



Geothermal gradient - 4°C/100m. Patterned area represents main zone of thermogenic hydrocarbon production (TTI - 15 to 160); dashed line indicates deepest occurrence of "wet" gas (TTI - 1500) according to Waples (1980).

Figure 49. LOPATIN BURIAL HISTORY RECONSTRUCTION OF MAGDALENA FAN AND ABYSSAL PLAIN OFFSHORE OF NORTHEASTERN COLOMBIA, ASSUMED SEDIMENTATION RATE IS 7cm/1000yr

Mann and Burke (1984) have claimed that the deformed belts resulted from the collision of South America and the Isthmus of Panama around 3.6 m.y. ago. Kellogg and Bonini (1981) estimated that along the Colombian continental margin, the Caribbean and South American plates are converging at a rate of 1.9 cm/yr. We have no good seismic control on exact basement depth and subduction angle in the area of the marginal deformed belt for which the estimate by Kellogg and Bonini (1981) of 1.9 cm/yr convergence was derived.

Assessment of Gas Resources in Gas Hydrates

The presence of gas hydrates in the sediments of the Colombia Basin has not been confirmed. Any assessment of potential gas resources trapped in or below gas hydrates must be based only on indirect evidence. By considering the geological factors reviewed in this study, estimates of relative gas hydrate potential in each surveyed area of the study region can be made. Using an in-place gas quantity formula derived in previous reports (Krason et al., 1986) resource estimates can be arrived at. The principal value of these figures are for comparison of in-place gas between areas within a study region and for comparison between study regions. There is no implication that the potential resource figures in this section represent economic reserves produceable under current economic conditions and technology. Since the gas quantity figures are intended mainly for comparison purposes, assumptions used in assessing previously studied regions will be continued here although there is no evidence that the porosity and degree of hydrate dissemination reflect the actual conditions of the Colombia Basin study region.

Nicaragua Rise

The sediments covering the Nicaragua Rise are all within the pressure-temperature stability limits for gas hydrates. The sediments are composed almost entirely of pelagic carbonates. DSDP Site 152 on the south flank of the Nicaragua Rise yielded carbonate sediments and rocks overlying igneous basement. These sediments were essentially barren of organic carbon. There is little evidence to suggest that a pre-uplift terrigenous sediment section exists anywhere on the Nicaragua Rise. Prell (1978) showed that the Pleistocene sediments sampled in 25 piston cores from the Nicaragua Rise are similar to those sampled at DSDP Site 152; pelagic carbonates are the exclusive lithology. The sediment thicknesses seen on seismic sections average much less than 1,000 m, thus precluding thermogenic gas generation. Although more thorough surveying may find isolated pockets of gas-bearing muds deposited prior to uplift, the outlook for gas hydrates on the rise is bleak. The thin organic-lean sediments have essentially no methane generative potential. The potential for significant deposits of gas hydrates on the Nicaragua Rise is so small that we shall consider it to be nil.

South Haitian Borderland

No published studies on the continental margin off the south coast of Haiti were found. Very little is known of the structure or stratigraphy of the region. Biju-Duval et al. (1983) claimed that an extension of the Muertos trench, the convergent margin south of eastern Hispanola, can be traced onshore in southern Haiti. The entire forearc and accretionary complexes were uplifted and are now exposed on the land surface of southern Haiti. From this, it can be inferred that the south Haitian Borderland is composed of block faulted sections of basin floor turbidites. These pre-uplift beds are probably now covered by a layer of pelagic and hemipelagic sediments. The uplift of the Hispanola convergent margin which produced present geology of the south Haitian Borderland is thought to be related to uplift of or collision with the Beata Ridge. The South Haitian Borderland resembles the Beata Ridge in probable structural and sedimentary styles. As such, this small province will be included with the Beata Ridge in assessment.

Beata Ridge

Beata Ridge covers 60,000 km^2 of the study region. The sediments of the Beata Ridge are at proper depths for gas hydrate stabilization. Two DSDP holes drilled on the Beata Ridge, Site 151 on the west flank and Site 153 on the gentler southern flank, penetrated Cenozoic sections of dominantly organic-lean carbonate pelagites and occasional hemipelagites. However, both sites yielded organic-rich Cretaceous sediments which had been deposited prior to uplift of the Beata Ridge. The exceedingly high organic carbon content of the pre-uplift sediments (up to 6.2% TOC) indicates that large amounts of kerogen with the potential to generate a substantial amount of gas exist deep in the section. However, no gas was reported while drilling these cores. Where this promisingly rich basal sediment layer does generate biogenic gas, it could be trapped in situ as hydrates. Alternatively, if the organic rich sediments are below the gas hydrate stability zone as at Site 153, such gas may migrate upward to the hydrate stability zone. Migration through the very fine-grained pelagic sediments of the upper part of the section would be very difficult. The abundant active and recently active faults in the Beata Ridge present possible migrational pathways for deep biogenic gas. Sediment depths on the Beata Ridge are insufficient for thermogenic gas generation.

Gas hydrate occurrences on the Beata Ridge would probably be small in area and widely separated. Since the potential gas generating zones are thin horizons rather than thick sections, any seismic evidence of Beata Ridge hydrates should coincide with sedimentary layering and not produce distinct BSRs. Small BSR "halos" may be expected in faulted areas where gas has the migrational freedom to disperse independently of stratal controls. Due to a lack of direct or indirect evidence of hydrates on the Beata Ridge, the hydrate potential of the ridge is low. Very rich potential source rocks suggest that some hydrates may exist. Based on these factors, the probable areal extent of gas hydrates beneath the Beata Ridge is assigned to be 1%.

In accord with previous reports, it will be assumed that the porosity of the hydrate stability zone is 43%. Hydrates, when present, are assumed to fill 12% of the pore space or occupy 5% of the rock volume. Ideally, a unit volume of pure gas hydrate could release 200 volumes of gas at 0° C and 1 atm. Although recent work on natural hydrates shows that this volumetric gas to hydrate factor may be too large, it is retained for consistency.

The calculated volume of gas trapped in gas hydrates on the Beata Ridge per meter thickness of 5% hydrated sediment is:

1 m thickness x 6 x 10^{10} m^2 area x 5% hydrate x
200 volume gas/volume hydrate x 1% areal extent =
6 x 10^9 m^3 (0.2 TCF)

The volume of gas contained in gas hydrates beneath the Beata Ridge for various assumed areawide mean thickness values for the hydrated layer is:

1 m = 6 x 10^9 m^3 (0.2 TCF)
10 m = 6 x 10^{10} m^3 (2 TCF)
100 m = 6 x 10^{11} m^3 (20 TCF)

Aruba Gap

The abyssal plain beneath the Aruba Gap covers a small area (8,000 km) but has a high potential for gas hydrates. A BSR extending across 70% of the width of the Aruba Gap was seen on seismic line B-3 (Figure 38). The BSR was evident not only on the multichannel seismic section but also on a single channel air gun profile collected simultaneously. As BSRs are very rarely found in single channel air gun records, the BSR in the Aruba Gap represents a major change in acoustic impedance of the sediment pile. An unconformity at 0.5 sec subbottom was reported in a nearby single channel line in a very similar geological setting to that illustrated in line B-3 (Moore and Fahlquist, 1976). The BSR on line B-3 appears to be an unconformity on casual inspection raising the possibility that the oddly coincident unconformity reported by Moore and Fahlquist (1976) may be a BSR. The poor quality of the published line prevented thorough reexamination of the data. Organic-rich Cretaceous rocks were cored at DSDP Site 153. The sediment section beneath the Aruba Gap should contain these same basal layers overlain by turbidites which may contain sizeable amounts of gas generative organic carbon. Faults abound in the area of the BSR on line B-3 (Case and Holcomb, 1980; Stoffa et al., 1981). This structural deformation may provide migrational paths for biogenic methane produced at greater depths than the base of the gas hydrate stability zone. Thermal modeling of the Aruba Gap has shown that there is little potential for thermogenic gas generation.

Based on the above factors we assign a probable areal hydrate extent of 16% to the sediments beneath the Aruba Gap. The volume of gas contained in gas hydrates per meter thickness of hydrated sediment is thus estimated as:

1 m thickness x 8 x 10^9 m^2 area x 5% hydrate x 200 volume
gas/volume hydrate x 16% areal extent =
1.3 x 10^{10} m^3 (0.5 TCF)

The volume of gas contained in gas hydrates beneath the Aruba Gap for various assumed areawide mean thickness values for the hydrated layer is:

1 m = 1.3×10^{10} m^3 (0.5 TCF)
10 m = 1.3×10^{11} m^3 (5 TCF)
100 m = 1.3×10^{12} m^3 (50 TCF)
500 m = 6.5×10^{13} m^3 (250 TCF)

Submarine Fans

The Magdalena and Panama-Costa Rica fans cover about 50,000 km^2 each. The exact size of each fan is arbitrary, as the boundary between lower fan and abyssal plain is gradational. Of the two, the Magdalena Fan is better studied and is composed of a thicker sedimentary pile. The fan areas would be expected to have sediments with adequate organic carbon. The very rapid fan sedimentation should lead to excellent preservation of organic matter. Slumping and growth faulting should provide structural pathways for gas migration. Additionally, the sediments under the landward areas of the Magdalena Fan are mature with respect to thermogenic gas generation. Mud diapirs exist under the Magdalena Fan and may provide active migrational conduits for gas.

The major negative factor for hydrate presence in the fans is a lack of BSRs. The strata and sea floor over most of the fan are so close in orientation as to make BSRs difficult to discern. Kolla et al. (1984) demonstrated that the Magdalena Fan was in many ways similar to the Mississippi Fan of the Gulf of Mexico in spite of its location on an active rather than a passive margin. Leg 96 of the DSDP cored extensively on the Mississippi Fan. The shipboard party included prominent gas hydrate researchers who examined the cores carefully for any sign of hydrates. Although a wide variety of geomorphologically different sites were drilled, no evidence of gas hydrates in the Mississippi Fan was found (Bouma et al., 1985). These are discouraging results for gas hydrate presence in deep sea fans in the Colombia Basin if the parallel between the Magdalena and Mississippi fans extends to similarity in environments of gas hydrate formation.

Although there are many factors favorable for hydrate formation in the sediments of the Colombia deep sea fans, the fact that no evidence has been found anywhere for gas hydrates in a clastic fan setting dominates our estimation of probable extent. Also, we know little about the geology of the Panama-Costa Rica Fan; the favorable factors identified in the Magdalena Fan may not exist in the western fan. Thus, we assign a 2.5% probable areal extent to hydrates in the fan environments.

The calculated volume of gas trapped in the form of gas hydrates in the deep sea fans of the Colombia Basin per meter thickness of 5% hydrated sediment is:

1 m thickness x 10^{11} m^2 area x 5% hydrate x 200
volume of gas/volume of hydrate x 2.5% areal extent =
2.5×10^{10} m^3 (0.9 TCF)

The volume of gas contained in gas hydrates beneath these deep sea fans for various assumed areawide values of the thickness of the hydrated layer is:

$$
\begin{aligned}
1 \text{ m} &= 2.5 \times 10^{10} \text{ m}^3 \text{ (0.9 TCF)} \\
10 \text{ m} &= 2.5 \times 10^{11} \text{ m}^3 \text{ (9 TCF)} \\
100 \text{ m} &= 2.5 \times 10^{12} \text{ m}^3 \text{ (90 TCF)}
\end{aligned}
$$

Abyssal Plain

The Colombia Basin abyssal plain extends over 300,000 km². The abyssal plain is covered principally by distal turbidites from the Magdalena Fan and the marginal deformed belts. An area with fewer turbidite seismic reflectors occurs south of the Hess escarpment west of 77° W latitude over basement highs. The main evidence for gas hydrates in the abyssal plain environment is the extremely gassy cores recovered from DSDP Site 154. The extensive disruption of the cored material by escaping gas suggests that gas hydrates may have been drilled at Site 154 but were not recognized as such. Miocene turbidites cored at DSDP Site 154 were very rich in organic matter. These same sediments can be traced elsewhere in the abyssal environment in seismic section. These sediments are found in the lower portion of the gas hydrate stability zone over much of the Basin. The abyssal sediments reach depths offshore of Colombia where active thermal gas generation should be occurring. Significant intraplate deformation in the abyssal plain in the form of faults has continued into the present (Case and Holcomb, 1980; Mann and Burke, 1984) which would provide possible gas migration routes. Evidence of gas hydrates recovered from basinal turbidites from the Gulf of Mexico was reported from DSDP Leg 10 (Krason et al., 1986). On line CT1-25 the acoustic transparency which occurs in marginal hydrate zones can be traced 15 km seaward from the margin. Thus hydrates should occur at least in a ring around the gas hydrate-rich marginal deformed belts. The occurrence of a BSR in the abyssal sediments of the nearby Aruba Gap also strengthens the case for gas hydrates in the main abyssal plains of the Colombia Basin.

Based on these favorable factors, a probable areal extent of gas hydrates in the large abyssal plain is estimated at 10%. The volume of gas contained in gas hydrates per meter of 5% hydrated sediment is:

1 m thickness x 3 x 10^{11} m² area x 5% hydrate x 200
volume of hydrates/volume of gas x 10% areal extent =
3 x 10^{11} m³ (11 TCF)

The volume of gas in abyssal plain sediments of the Colombia Basin for various assumed areawide mean thickness values for the hydrated layer is:

$$
\begin{aligned}
1 \text{ m} &= 3 \times 10^{11} \text{ m}^3 \text{ (11 TCF)} \\
10 \text{ m} &= 3 \times 10^{12} \text{ m}^3 \text{ (110 TCF)} \\
100 \text{ m} &= 3 \times 10^{13} \text{ m}^3 \text{ (1,100 TCF)} \\
300 \text{ m} &= 10^{14} \text{ m}^3 \text{ (3,300 TCF)} \\
500 \text{ m} &= 1.5 \times 10^{14} \text{ m}^3 \text{ (5,500 TCF)}
\end{aligned}
$$

Marginal Deformed Belts

The marginal deformed belts north of Panama and Colombia have a convincing body of evidence that indicates an abundance of gas hydrates.

Very distinct and laterally continuous BSRs are recorded on nearly all high quality seismic lines crossing the marginal deformed belts. The BSRs tend to be strongest over the lower continental slope and to die out in the forearc basin. The deformed margin will be divided into three subprovinces for assessment, as was done in the thermal maturity section.

North Panama Deformed Belt. This area covers 36,000 km² between 77° W and 81° W. Each of the seven high quality seismic profiles crossing the North Panama Deformed Belt displayed BSRs. The BSRs are continuous beneath the structural highs of the accretionary wedge and continue landward through the forearc basins to a minimum water depth of 1,800 m. We conservatively estimate that 55% of the North Panama Deformed Belt in water deeper than 500 m is underlain by gas hydrates.

South Caribbean Deformed Belt Offshore of Northwest Colombia between 76° W and 77° W covers 6,000 km². The good seismic coverage shows that BSRs are abundant, but not as continuous along strike. Up to 50% of the margin as shown in some sections is underlain by BSRs; less than 5% of others shows BSRs. Active thermogenic gas generation is occurring under the accretionary belt. Structural conduits for migration should exist in the strongly deformed sediments. Due to the lack of continuity of BSRs, a probable areal extent of 30% is assigned to this area.

South Caribbean Deformed Belt Offshore of Northeast Colombia covers approximately 40,000 km² between 72° W and 74.5° W. Strong BSRs were noted in all seismic lines. These BSRs are generally restricted to seaward of the forearc basin. The sediment pile beneath this portion of the margin is very thick; the deeper sediments are thermally mature with respect to gas generation beneath this section of the deformed belt. The western part of this area exhibits extensive mud diapirism which may be linked to methane generation and migration; a faint reflector, possibly a hydrate BSR, was noted near a diapir in this area. The BSRs in this section are very strong over the accretionary prism, but tend to not be evident at water depths of less than 2,500 m.

Since nearly all the BSRs are located beneath water deeper than 2,500 m and much of this area is composed of sea floor beneath 500 - 2,400 m, a probable extent of hydrated sediments of 40% is estimated.

An estimate of the gas contained in the marginal deformed belts along the southern border of the region can be calculated as the sum of the estimates for each. Thus the gas volume trapped in gas hydrates per meter thickness of 5% hydrated sediment is:

$$1 \text{ m thickness} \times 5\% \text{ hydrates} \times 200 \text{ volume gas/volume hydrates} \times (3.6 \times 10^{10}\,\text{m}^2 \text{ area} \times 55\% \text{ areal extent} + 6.5 \times 10^{9}\,\text{m}^2 \text{ area} \times 30\% \text{ areal extent} + 4 \times 10^{10}\,\text{m}^3 \text{ area} \times 40\% \text{ areal extent}) = 4 \times 10^{11}\,\text{m}^3 \text{ (12 TCF)}$$

We have no evidence as to the vertical extent of the hydrated zone which caused the BSRs upon which this volumetric estimate is based. The gas volumes contained beneath the entire marginal deformed belt province of the study region for various assumed areawide mean vertical thickness values is:

$$
\begin{aligned}
1 \text{ m} &= 4 \times 10^{11} \text{ m}^3 \text{ (12 TCF)} \\
10 \text{ m} &= 4 \times 10^{12} \text{ m}^3 \text{ (120 TCF)} \\
100 \text{ m} &= 4 \times 10^{13} \text{ m}^3 \text{ (1,200 TCF)} \\
300 \text{ m} &= 1.2 \times 10^{14} \text{ m}^3 \text{ (3,600 TCF)}
\end{aligned}
$$

Data Gaps

The seismic evidence for gas hydrates in the Colombia Basin study region is overwhelming. A large number of high quality multichannel seismic lines show BSRs over the deformed margins and occasionally beneath the abyssal plain. Many of the adjacent seismic lines show different degrees of BSR expression which complicates the assignment of probable areal extent. Results from this study indicating that migrated seismic lines tend to display marginal BSRs more convincingly than unmigrated versions were recently corroborated by the findings of Miller and von Heune (1986). Therefore it is suggested that reprocessing of unmigrated seismic data may show that BSRs do exist in areas previously thought to be devoid of BSRs. Of course, more extensive seismic coverage would be of great help in delineating the areas with greatest hydrate potential. It is recommended that future surveys include lines parallel to the trend of the continental margin which would permit greater certainty in determining lateral continuity of BSRs, and additionally, the amount of structural closure beneath the BSRs which could control the volume of free gas possibly trapped. Although Shipley et al. (1979) indicated that no resolvable velocity anomaly was associated with BSRs on lines CT1-21 and CT1-25, a more thorough velocity comparison between nearby lines with different degrees of BSR expression (eg. CT1-25 and CT1-27) may clarify the thickness of the hydrate zone responsible for the BSR. Based on the observation by Shipley et al. (1979) that BSRs differ from sediment reflectors in polarity, a detailed analysis of the parallel reflections on the abyssal plain in areas projected to contain hydrates may further elucidate hydrate extent. The negative polarity of the BSR reflection may allow a hydrate boundary to be picked where sediments and the sea floor are concordant; a polarity inversion of a reflector may serve as a criterion for gas hydrate presence in places where discordance is precluded by the morphology of the sedimentary pile. Since high energy single channel sparker data is sensitive to BSR presence (Krason et al., 1986), perhaps a survey which is specifically seeking to delineate hydrates could use this more cost-effective method rather than traditional CDP multichannel methods.

Drilling is needed in the Colombia Basin study region to verify hydrate presence and to refine stratigraphic interpretations. Although it is possible that hydrates were unknowingly drilled at DSDP Site 154, use of a pressure core barrel by a crew familiar in gas hydrate recognition could possibly substantiate the abundant indirect evidence for hydrates. Since the locations of the DSDP sites in the study region were selected principally based on biostratigraphic suitability, there is a major lack of data on the age, lithology, and gas generative potential of the terrigenous sediments which constitute the vast majority of the study region. Additional coring in these more common sedimentary settings which have been projected to be more suitable for gas hydrates should prove fruitful. Hopefully additional measurements which were not included in DSDP legs in the region could be incorporated in these drill holes. Down hole pressures, temperatures, pore water chemistry, and wireline logs would provide additional data for use in further assessing gas hydrate resources and formation parameters, and in developing practical production strategies.

The presence of mud diapirism near seismically inferred gas hydrate locations is intriguing. Such structures are common along other convergent margins which show evidence of gas hydrates (e.g. Makran, Timor, New Zealand, Aleutians). The correspondence of mud diapirism and gas hydrates may be coincidental. Analysis of gases from Colombian mud volcanoes and gas seeps may further understanding of the degree to which sedimentary diapirism and gas hydrates are associated.

Conclusions

In the Colombia Basin study region, gas hydrates are strongly indicated by unusually distinct BSRs in deformed sediments in the lower continental slopes offshore of Panama and Colombia. Selection of this study region was based on two seismic lines described by Shipley et al. in 1979. Subsequently these lines were published by Lu and McMillen (1983). Three additional seismic lines from the study region with BSRs identified were published by Ladd et al. (1984). In the course of this study we have greatly enlarged the collection of seismic lines showing BSRs. From the five lines with BSRs known at the outset of this study, at least 19 seismic lines with probable BSRs are now identified. Furthermore, we would suspect that most, if not all, of the five additional seismic lines crossing the marginal deformed belts from the CT1 series, which are still held as proprietary by the University of Texas Institute for Geophysics, will show BSRs. One of the most significant findings of this regional study is a BSR in undeformed abyssal plain sediments. This tends to strengthen our inference of a thick, areally extensive gas hydrate deposit in a similar abyssal setting in the western Gulf of Mexico (Krason et al., 1986).

The wealth of BSRs in this region has allowed detailed comparisons of the depths of occurrence of BSRs with theoretical models. These comparisons suggest that changes in geothermal gradient and/or pressure gradient exists across the convergent margins. These findings may eventually be of use in elucidating the differing tectonic regimes present along the marginal deformed belt, once control is obtained by drilling.

The dearth of relevant drilling data permits few conclusions on probable gas hydrate source and host rocks. Turbidites dominate the seismic sections of the areas with high gas hydrate potential, but the resolution of seismic sections does not allow a more refined interpretation.

The Colombia Basin appears to be a major gas hydrate province which can serve as a model for assessment of less well studied regions. The abundant seismic evidence can be linked with the extreme gassiness of terrigenous sediments from DSDP Site 154 to suggest that gas hydrates may be widespread. The available seismic coverage over the margins is considerable. The proportion of seismic lines which display BSRs is large. The occurrence of BSRs appears to be more widespread in the Colombia Basin study region than at any other convergent margin currently being investigated. Whereas large quantities of gas hydrates have been identified in areas of the Middle America Trench which are devoid of BSRs, the Colombia Basin margin seismic lines show demonstrably extensive BSRs. Although verification must await drilling, it is possible that the high degree of BSR development in the Colombia Basin study region may indicate that a high rate of gas migration is delivering gas to the hydrate stability zone from below. Other convergent margins with fewer BSRs, but with other evidence of gas hydrates may represent scenarios wherein the gas becomes trapped in hydrates as it is generated without significant migration.

Of the many geological environments examined in the Colombia Basin study region, only the abyssal plain and deformed margin hold high potential for economic gas hydrate deposits. Nicaragua Rise and Beata Ridge have neither seismic nor drilling evidence of gas generative potential necessary for gas hydrate formation. The abyssal plain turbidites have proven high gas generation potential. The lack of sea floor relief over most of the abyssal plain precludes detection of seismic evidence of gas hydrates. The marginal deformed belt displays widespread seismic evidence of gas hydrates, but little direct evidence of gas generative potential of the sediments exists. The sediments in the gas hydrate stability zone of the deformed continental margin were largely accreted and deformed abyssal turbidites which by analogy should have gas generative potential. Additionally, the sediment pile beneath the deformed margin is very thick. If the accretionary process has been operating for a sufficiently long time, these thick marginal sections may have attained thermal maturity and thus be capable of augmenting shallow biogenic gas in the hydrate stability zone with migrated thermogenic gas. The compressional features of the marginal deformed belts have resulted in sea floor relief which creates very favorable conditions for development of substantial relief at the base of the gas hydrate stability zone. Thus large anticlinal traps beneath an impermeable gas hydrate interval may be formed in the accretionary complexes of the marginal deformed belts. This possibility of unconventionally trapped free gas combined with the extensive areal continuity of BSRs, relatively shallow water depths (1,600 - 3,800 m), and the proximity to onshore production facilities indicate that the marginal deformed belts offshore of Panama and Colombia is the most favorable area of the study region for eventual economic development of the gas hydrate resource.

REFERENCES

Bader, R. G., Gerard, W. E., Benson, W. E., Bolli, H. M., Hay, W. W., Rothwell, W. T., Ruef, M. H., Riedel, W. R., and Sayles, F. L., 1970, Initial Reports of the Deep Sea Drilling Project, v. 4: U. S. Govt. Printing Office, 753 p.

Biju-Duval, B., Bizon, G., Mascle, A., and Muller, C., 1983, Active margin processes: field observations in Southern Hispanola, in Watkins, J. S., and Drake, C. L., Studies in Continental Margin Geology: Am. Assoc. Petroleum Geologists Mem. 34, p. 325 - 347.

Biju-Duval, B., Mascle, A., Montadert, L., and Wanneson, J., 1978, Seismic investigations in the Colombia, Venezuela, and Grenada Basins, and on the Barbados Ridge for future IPOD drilling: Geologie en Mijnbouw, v. 57, p. 105 - 116.

Bode, G. W., 1973, Carbon and carbonate analyses, Leg 15, in Edgar , N. T., Saunders, J. B., et al., 1973, Initial Reports of the Deep Sea Drilling Project, v. 15: U. S. Govt. Printing Office, Washington, p. 1129 - 1137.

Bowin, C., 1976, Caribbean gravity field and plate tectonics: Geol. Soc. Am. special paper 169, 79 p.

Bowland, C., 1984, Seismic stratigraphy of the western Colombian Basin (Abst.): Am. Assoc. Petroleum Geologist Bull., v. 68, n. 4, p. 456.

Broecker, W., 1973, Interstitial water studies Leg 15 - introduction and summary; in Edgar, N. T., Saunders, J. B., et al., Initial Reports of the Deep Sea Drilling Project, v. 15: U.S. Govt. Printing Office, Washington, p. 1069 - 1073.

Burke, K., Cooper, C., Dewey, J. F., Mann, P., Pindell, J. L., 1984, Caribbean tectonics and relative plate motions, in Bonini, W. E., Hargraves, R. B., and Shagam, R., eds., The Caribbean-South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir 162, p. 31 - 64.

Burke, K., Fox, P. J., and Sengor, A. M. C., 1978, Buoyant ocean floor and the evolution of the Caribbean: J. Geophysical Research, v. 83, p. 3949 - 3954.

Case, J. E., 1974, Oceanic crust forms basement of eastern Panama: Geological Society of America Bulletin, v. 8, p. 645 - 652.

Case, J. E., 1975, Geophysical studies in the Caribbean Sea, in Nairn, A. E. M., and Stehli, F. G., eds., Ocean basins and margins, v. 3, The Gulf of Mexico and Caribbean Sea: New York, Plenum Press, p. 107 - 180.

Case, J. E., and Holcombe, T. L., 1980, Geologic-tectonic map of the Caribbean region: U. S. Geological Survey Miscellaneous Investigations Map I-1100.

Case, J. E., Holcombe, T. L., and Martin, R. G., 1984, Map of geologic provinces in the Caribbean region, in Bonini, W. E., Hargraves, R. B., Shagam, R., eds., The Caribbean-South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir 162, p. 1 - 30.

Claypool, G. E., Presley, B. J., and Kaplan, I. R., 1973, Gas analyses in sediment samples from legs 10, 11, 13, 15, 18, and 19, in Creager, J. S., Scholl, D. W., Initial Reports of the Deep Sea Drilling Project, vol. 19: Washington, U. S. Govt. Printing Office, p. 879 - 884.

Colsa, 1983, Wildcat Map of Colombia: Bogota.

Duncan, R. A., and Hargraves, R. B., 1984, Plate tectonic evolution of the Caribbean in the mantle reference frame, in Bonini, W. E., Hargraves, R. B., Shagam, R., eds., The Caribbean-South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir 162, p. 81 - 93.

Duque-Caro, H., 1979, Major structural elements and evolution of northwestern Colombia, in Watkins, J. S., Montadert, L., and Dickerson, P. W., eds., Geological and Geophysical Investigations of Continental Margins: Am. Assoc. Petroleum Geologists Mem. 29, p. 329 - 352.

Duque-Caro, H., 1984, Structural style, diapirism, and accretionary episodes of the Sinu-San Jacinto terrane, southwestern Caribbean borderland, in Bonini, W. E., Hargraves, R. B., Shagam, R., eds., The Caribbean-South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir 162, p. 303 - 316.

Edgar, N. T., Ewing, J. I., and Hennion, J., 1971, Seismic reflection and refraction in the Caribbean Sea: Am. Assoc. Petroleum Geologists Bull., v. 55, p. 833 - 870.

Edgar, N. T., Saunders, J. B., et al., 1973, Initial Reports of the Deep Sea Drilling Project, v. 15: U. S. Govt. Printing Office, Washington, 1137 p.

Epp, D., Grim, P. J., and Langseth, M. G., 1970, Heat flow in the Caribbean and Gulf of Mexico: Journal of Geophysical Research, v. 75, p. 5655 - 5669.

Fox, P. J., and Heezen, B. C., 1975, Geology of the Caribbean crust, in Nairn, A. E. and Stehli, F. G., eds., Ocean Basins and Margins, v. 3, The Gulf of Mexico and the Caribbean: New York, Plenum Press, p. 421 - 466.

Gardner, J. V., 1982, High resolution carbonate and organic carbon stratigraphies for the late Neogene and Quaternary from the western Caribbean and eastern equatorial Pacific, in Prell, W. L., Gardner, J. V., et al., 1982, Initial Reports of the Deep Sea Drilling Project, V. 68: U. S. Govt. Printing Office, p. 347 - 364.

Geotimes, 1976, News notes: v. 21, n. 12, p. 28.

Helminski, S. J., 1975, Temperature, Salinity, Oxygen, and Phosphate in Waters off Eastern Central America and Northern South America: National Oceanographic Data Center, NOAA, Washington, 189 p.

Harding, T. D., and Lowell, J. D., 1979, Structural styles, their plate tectonic habitats, and hydrocarbon traps in petroleum provinces: Am. Assoc. Petroleum Geoloists Bull., v. 63, p. 1016 - 1058.

Hedberg, H. D., 1974, Relation of methane generation to undercompacted shales, shale diapirs, and mud volcanoes: Am. Assoc. Petroleum Geologists Bull., v. 58, p. 661 - 673.

Hedberg, H. D., 1980, Methane generation and petroleum migration, in Roberts, W. H. and Cordell, R. D., eds., Problems of Petroleum Migration: Am. Assoc. Petroleum Geologists Studies in geology #10, Ann Arbor, Edwards Brothers, p. 179 - 206.

Holcombe, T. L., 1977, Caribbean bathymetry and sediments, in Weaver, J. D., ed., Geology, geophysics, and resources of the Caribbean, Report of the IDOE Workshop on the geology and marine geophysics of the Caribbean region and its resources, Kingston, Jamaica, 1975: University of Puerto Rico, Mayaquez, p. 27 - 62.

Holcombe, T. L., and Moore, W. S., 1977, Paleocurrents in the eastern Caribbean: geological evidence and implications: Marine Geology, v. 23, p. 35 - 56.

Hopkins, H. R., 1973, Geology of the Aruba Gap abyssal plain near DSDP Site 153, in Edgar, N. T., Saunders, J. B., et al., 1973, Initial Reports of the Deep Sea Drilling Project, v. 15: U. S. Govt. Printing Office, Washington, p. 1039 - 1050.

Kellogg, J. N., and Bonini, W. E., 1982, Subduction of the Caribbean Plate and basement uplifts in the overriding South American plate: Tectonics, v. 1, p. 251 - 276.

Kolla, V., Buffler, R. T., and Ladd, J. W., 1984, Seismic stratigraphy and sedimentation of Magdalena Fan, southern Colombian Basin, Caribbean Sea: Am. Assoc. Petroleum Geologists Bull., v. 68, n. 3, p. 316 - 332.

Krason, J., Finley, P. D., and Rudloff, B., 1986 (in press), Basin Analysis, Formation and Stability of Gas Hydrates in the Western Gulf of Mexico: U.S. Dept. of Energy, 168 p.

Krause, D. C., 1971, Bathymetry, geomagnetism, and tectonics of the Caribbean Sea north of Colombia, in Donnelly, T. W., ed., Caribbean Geophysical, Tectonic, and Petrologic Studies: Geological Society of America Memoir 130, p. 35 - 54.

Kuuskraa, V. A., Hammershaimb, E. C., Holder, G. D., Sloan, E. D., 1983, Handbook of Gas Hydrate Properties and Occurrence: U.S. Department of Energy, DOE/MC/19239-1546, U.S. G.P.O., Washington, 234 p.

Ladd, J. W. and Truchan, M., 1983, Compressional features across the Caribbean margin of Colombia, in Bally, A. W., ed., Seismic Expression of Structural Styles: Am. Assoc. Petroleum Geologists studies in geology series #15, v. 3, p. 3.4.2-163 - 3.4.2-166.

Ladd, J. W., Truchan, M., Talwani, M., Stoffa, P. L., Buhl, P., Hontz, R., Mauffret, A., and Westbrook, G., 1984, Seismic reflection profiles across the southern margin of the Caribbean, in Bonini, W. E., Hargraves, R. B., and Shagam, R., eds., The Caribbean-South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir 162, p. 153 - 160.

Lehner, P., Doust, H., Bakker, G., Allenbach, P., and Gueneau, J., 1983, Active margins - Caribbean margin of South America, in Bally, A. W., ed., Seismic Expression of Structural Styles: Am. Assoc. Petroleum Geologists studies in geology series #15, v. 3, p. 3.4.2-111 - 3.4.2-128.

Lu, R. S., and McMillen, K. J., 1982, Multichannel seismic survey of the Colombia Basin and adjacent margins, in Watkins, J. S., and Drake, C. L., eds., Studies in Continental Margin Geology: Am. Assoc. Petroleum Geologists Mem. 34, Tulsa, p. 395 - 410.

Ludwig, W. J., Houtz, R. E., and Ewing, J. I., Profiler-Sonobuoy measurements in Colombia and Venezuela basins, Caribbean Sea: Am. Assoc. Petroleum Geologists Bull., v. 59, p. 115 - 123.

Mann, P., and Burke, K., 1984, Neotectonics of the Caribbean: Reviews of Geophysics and Space Physics, v. 22, p. 309 - 362.

Mattson, P., 1984, Caribbean structural breaks and plate movements, in Bonini, W. E., Hargraves, R. B., and Shagam, R., eds., The Caribbean-South American Plate Boundary and Regional Tectonics: Geological Society of America Memoir 162, p. 131 - 152.

Miller, J. J., and von Huene, R. E., 1986, Analysis of seismic reflection lines over Pacific convergent margins (abs): U.S.G.S. Research on Energy Resources, Programs and Abstracts, U.S.G.S. Circular 974, p. 24.

Minster, J. B., and T. H., Jordan, 1978, Present day plate motions: J. Geophysical Research, v. 83, p. 5331 - 5354.

Moore, G. T., and Fahlquist, D. A., 1976, Seismic profile tying Caribbean DSDP Sites 153, 151, and 152: Geol. Society Am. Bull., v. 87, p. 1609 - 1614.

National Ocean Survey, National Oceanographic and Atmospheric Administration, 1981, Bathymetric map of the Caribbean region, compiled by Flanagan, J. P., Golg, J. G., Jones, C. R., Marchant, F. L., Murchison, R. R., Rebman, J. H., Snodgrass, L. W., Sorenson, F. H., and Whitney, J. C., Scale 1:2,500,000.

Normark, W. R., 1978, Fan valleys, channels, and depositional lobes on modern submarine fans: Characters for recognition of sandy turbidite environments: Am. Assoc. Petroleum Geologists Bull., v. 62, p. 912 - 931.

Olawsson, E., 1960, Description of sediment cores from the Indian Ocean: Swedish Deep-Sea Expedition Reports, v. 9, n. 2, p. 53 - 88.

Pindell, J., and Dewey, J. F., 1982, Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region: Tectonics, v. 1, p. 179 - 211.

Prell, W. L., 1978, Upper Quaternary sediments of the Colombia Basin: spatial and stratigraphic variation: Geological Society of America Bull., v. 89, p. 1241 - 1255.

Prell, W. L., Gardner, J. V., et al., 1982, Initial Reports of the Deep Sea Drilling Project, V. 68: U. S. Govt. Printing Office, 495 p.

Saunders, J. B., Edgar, N. T., Donnelly, T. W., Hay, W. W., 1973, Cruise Synthesis, in Edgar, N. T., Saunders, J. B., et al., 1973, Initial Reports of the Deep Sea Drilling Project, v. 15: U. S. Govt. Printing Office, Washington, p. 1077 - 1112.

Seeley, D. R., 1979, The evolution of structural highs bordering major forearc basins, in Watkins, J. S., Montadert, L., and Dickerson, P. W., eds., Geological and Geophysical Investigations of Continental Margins: Am. Assoc. Petroleum Geologists Mem. 29, p. 245 - 260.

Shepard, F. P., Dill, R. F., and Heezen, B. C., 1968, Diapiric intrusions in foreset slope sediments off Magdalena Delta, Colombia: Am. Assoc. Petroleum Geologist Bull., v. 52, p. 2197 - 2207.

Shepard, F. P., 1973, Sea floor off Magdalena Delta and Santa Marta area, Colombia: Geological Society of America Bull., v. 84, p. 1955 - 1972.

Shipley, T. H., Houston, M. H., Buffler, R. T., Shaub, F. J., McMillen, K. J., Ladd, J. W., Worzel, J. L., 1971, Seismic evidence for widespread possible gas hydrate horizons on continental slopes and rises: Am. Assoc. Petroleum Geologists Bull., v. 63, p. 2204 - 2213.

Silver, E. A., Case, J. H., and MacGillavry, H. J., 1975, Geophysical study of the Venezuelan Borderland: Geological Society of America Bull., v. 86, p. 213 - 226.

Stoffa, P. L., Mauffret, A., Truchan, M., and Buhl, P., 1981, Sub-B" Layering in the southern Caribbean: The Aruba Gap and Venezuela Basin: Earth and Planetary Science Letters, v. 53, p. 131 - 147.

Sykes, L. R., McCann, W. R., and Kafka, A. L., 1982, Motion of the Caribbean plate during last 7 million years and implications for earlier Cenozoic movements: Journal of Geophysical Research, v. 87, p. 10656 - 10676.

Talwani, M., Ewing, J., Ewing, M., and Saito, T., 1966, Geological and geophysical studies of the Caribbean submarine escarpment (abs.): Geological Society of America Special Paper 101, p. 217 - 218.

Tissot, B. P., and Welte, D. H., 1978, Petroleum Formation and Occurrence: Springer Verlag, Berlin, 696 p.

von Huene, R., and Lee, H., 1983, The possible significance of pore fluid pressures in subduction zones, in Watkins, J. S. and Drake, C. L., Studies in Continental Margin Geology: Am. Assoc. Petroelum Geologists Mem. 34, p. 781 - 791.

Waples, D. W., 1983, Reappraisal of anoxia and organic richness with emphasis on the Cretaceous of North Atlantic: Am. Assoc. Petroleum Geologists Bull., v. 67, p. 963 - 979.

Weast, R. C., ed., 1976, Handbook of Chemistry and Physics, 56th edition: CRC Press, Cleaveland, p. E-11 - E-16.

Zimmerman, H. B., 1982, Lithologic stratigraphy and clay mineralogy of the western Caribbean and eastern equatorial Pacific, in Prell, W. L., Gardner, J. V., et al., 1982, Initial Reports of the Deep Sea Drilling Project, V. 68: U. S. Govt. Printing Office, p. 383 - 396.